



# A review on coastal erosion and flooding risks and best management practices in West Africa: what has been done and should be done

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## Abstract

The West African coast is vulnerable to natural hazards and human interventions. Although various measures have been taken at different scales, mostly at the local level, there is a need to improve management at the regional level. We examine these actions and possible solutions from different perspectives and provide conclusions and recommendations on the integration of solutions to improve coastal management. From North West Mauritania to across the Gulf of Guinea a system of coastal zoning that can be managed holistically is encouraged. The development of holistic planning is seen as a sustainable approach to management that seeks to link users/processes together rather than focus on a single particular issue and solution. Strengthening, monitoring, promoting the observation network and generalising open data centralisation and exchange for a better understanding of coastal dynamics and pressures is encouraged. There is a need for capacity building, expertise and federative actions. Furthermore, the need to identify and involve not only stakeholders, but also communities and scientists with multilevel inputs. All must agree on coordinated plans to achieve stakeholder objectives, using an approach adapted to the multi-spatial scale (e.g at the scale of sediment cells, integrating from the sources of sediment in river basins to their redistribution along the coast, perturbed by climate changes and anthropic stresses), so that only regional solutions are appropriate and will be effective. These must follow sustainable strategies with a multi-temporal sequenced solution and anticipate changes, or adaptive solutions using solutions in synergy with different time frames as well as managing natural and human systems responsibly. A plan that considers changes in coastal systems and anticipates impacts and adapts plans accordingly will be key.

**Keywords** West Africa · Ecosystem-based management · Coastal hazards · Coastal vulnerability · Coastal Defence

## Introduction

The West African coastline covers some 6000 km and includes 14 countries, from Mauritania to Sao Tome and Principe. This coastal area constitutes about 6 deltas (Anthony 1995), several rivers and wetlands from Senegal to Gabon. The West African coast from Mauritania to south of Guinea (between Sierra Leone and the Niger Delta) is characterised by linear sand barriers. These sand barriers are built by energetic longshore drift following long and regular sea-swell waves (Almar et al. 2015, 2019; Anthony 2015; Anthony et al. 2016, 2019; Ndour et al. 2017). This part of the coast is interspersed with sandy beach ridges between south of Senegal and Sierra Leone. The central and southern coast of West Africa throughout the Bight of Benin, became infilled between 6000 and 4000 B.P. with sand; the coastal longshore drift developed into a single-celled system with the major source of sand from the Volta Delta in Ghana. Sand

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from the Volta Delta could be distributed to almost 300 km long of the coastal stretch (Blivi et al. 2002) in the Gulf of Guinea. This stretch of the West coast is mostly sandy with few rock outcrops and a small proportion of muddy areas (e.g. Dada et al. 2020) associated with open estuaries, and relatively larger tidal ranges. This coastal area particularly in the Bight of Benin was stable. This stability became perturbed by mostly human activities such as the construction of deep water ports and dams (Almar et al. 2015; Anthony et al. 2019; Aman et al. 2019).

It is widely known that the coastal area of West Africa hosts vital natural resources as well as habitats that provide critical ecosystem services (Faye 2010a, b). The coastal area of West Africa is home to about a third of the population in the region and generates 56% of its Gross Domestic Product (World Bank 2019). The resources within the coastal environment are critical for the performance of the shoreline, to ensure the protection against coastal erosion, contamination, sea level anomaly and severe weather events. Yet its coastline is particularly vulnerable because of a mixture of increasing natural hazards, anthropogenic activities and a constellation of pressures (Faye 2010a, b; Maanan et al. 2018). The risks including erosion, which are still persistent, could rise in the coming decades because the changes in climate and human behaviour exacerbate them, unless sustainable interventions are attained. The shorelines of West Africa have evolved at a faster and sporadic rate in recent years (Thior et al. 2019; Angnuureng et al. 2020). Data related to oceanic forcing (waves, sea level and tidal variation), hydrology (e.g. rainfall) and the status of the coast (its geology, morphology and coastal recession) show that knowledge on the vulnerability of this coastal area is key to socio-economic development (Apeaning Addo 2009; Boateng 2009).

Coastal risks are mostly associated with hazards such as flooding, high winds and waves, coastal erosion, storm surges and human development along the coast (Thior et al. 2019). The West Africa coastal area is complex, exposed to diverse waves coming from different directions. Many parts of the coastal area of West Africa currently experience accelerated degradation related to coastal erosion and inundation as a result of the strengthening of extreme climatic factors (Aman et al. 2019; Thior et al. 2019; Angnuureng et al. 2020). This coastal erosion process, especially of sandy and muddy coasts (Anthony 2006; Dada et al. 2020) comprise one of the predominant factors in the degradation along the entire coast.

Adaptation investments are needed along the coastline to ensure that vulnerable areas are protected from coastal hazards. Various governments have implemented solutions albeit locally to manage coastal degradation. Risk reduction through physical, nature-based and integrated policy/regulatory solutions to reduce the vulnerability of areas, particularly human settlements, economic activities and natural resources to the multitude of coastal hazards is vital. The exchanges between

natural and built features (both existing and planned) within the coastal system are vital factors that determine susceptibility, steadiness, threat and resilience of coasts. Many countries have applied various approaches to combat coastal vulnerability. For example, a number of coastal defence systems such as groynes, jetties, seawalls and breakwaters (Angnuureng et al. 2013; Laïbi et al. 2014) can be found on the coastlines in the Bight of Benin as well as on the coastline of Côte d'Ivoire, Gambia and Senegal (Ndour et al. 2017). Despite the interventions, rates of coastal erosion within the individual countries continue to rise. This suggests that isolated/local solutions may not be the resultant approaches as they will lead to consequential effects on adjacent beaches. The likelihood of a particular hazard arising within different areas is unique because most hazards depend on variables such as geomorphology, weather conditions, topo-bathymetry and land cover/use spatial planning. For certain types of hazards, the whole community will have parallel vulnerability. In other hazards such as floods, each community may be affected with a unique magnitude; example, low-lying coastal communities would be more vulnerable to inundation. Therefore, adaptation responses are essential for as several hazards as conceivable to clearly present the specific features and local location variables that will become key concerns when developing mitigation strategies.

Coastal natural geomorphology and managements and policies are tied together as the resulting regional variation is in part hinged on a set of environmental variables that have hardly been identified: regional differences in climate with impacts on coastal dynamics, regional differences in continental shelf width that in turn drive differences in waves and tidal range between the sandy-muddy-sandy transitions aforementioned, regional differences in river basin management that impact on interception of sediment supply to the coast. These regional differences have a strong bearing on coastal vulnerability and management aspects. It is useful embarking on an example of ecosystem-based management with the example of the Volta delta, but a major problem facing the sandy coastal sectors is that of erosion hinged on gradients in longshore sand transport by waves that has been considerably perturbed by ports in particular. A convenient framework for looking at this erosion and the attendant vulnerability problem is that of coastal sediment budgets and coastal sediment cells (see, for instance Anthony et al. 2019) which implies an international sub-regional joint effort to fight the causes of erosion and find common mitigation strategies.

Even if all solutions have not been tested in West Africa, coastal management has been done in different forms with a wide range of hard and soft engineering solutions, coastal planning techniques and nature-based solutions, mostly at local scale. Vulnerability of the coastal areas to natural events and man-made factors has been addressed following hard approaches (European Commission 2004; Angnuureng et al.

2013) such as revetments, jetties, seawalls and groynes, and soft approaches including revegetation and beach nourishment (e.g. Turner and Leatherman 1997; French 2001; European Commission 2004) in attempts to control coastal erosion, yet these methods are debatable. For instance, when hard engineering solution is used, the portion of the beach further down the coast will not receive sufficient beach material leading to large erosion (Angnuureng et al. 2013; Ndour et al. 2017), while soft methods are transient as sand will always be conveyed around the coast by cross-shore and alongshore drifts. Anytime the solutions applied are unsuitable, not designed properly or not sustained, the problem of erosion is aggravated, due to a lack of regional sediment-cell scale coordination between different actors such as municipality, region, state and neighbouring countries. This challenge is compounded if the effects on nearby beaches are not prudently assessed. This can further be made complex by the lack of adequate monitoring.

The lack of adequate policy, regulatory and institutional frameworks during urbanisation and access to or use of resources; deficits in environmental awareness and health conditions; and insufficient incentives for conserving and managing the environment are the root cause of coastal degradation and destructive socio-economic challenges. To ensure risk reduction, it is best a combination of hazard management options are employed. Competition for natural resources and living space from a growing number of coastal communities, exacerbated by pollution from industrial and domestic waste, is intensifying the pressure on coastal and marine habitats in West Africa from the rapid transformation of vast areas for economic growth (Thior et al. 2019). Several coastal nations in the subregion are following aggressive industrial growth approaches. These approaches can encourage or enable the propagation of poorly planned and managed settlements and coastal tourism, leading not only to coastal erosion and ecosystem deprivation, but also to the loss of economic benefits that could be provided by well-planned private and environmentally sustainable investment (Apeaning Addo 2009).

This paper is an initiative to provide objective information to address coastal vulnerability in West Africa. The study conducts desktop study of 14 coastal countries in West Africa to outline the consequences of all major human interventions in relation to recurrent erosion and changes in climate within such an enormous coastal area. The outcomes of this study will present basis to improve implementation of the anthropogenic interventions (i.e. port jetties and river dams) and actions towards changes in climate (i.e. sea level rise, changes in wave climate, precipitation and temperature) by local authorities and organisations within this shared ecosystem (Giardino et al. 2018). Various damaging effects occur in several countries (Ndour et al. 2017; Anthony et al. 2016, 2019). From this study, and with support from various technical expertise, a proposal of a good but regional coastal

management plan for the entire region could be developed. Having presented the existing approaches, the current challenge of this document is to present an overview of approaches applied locally in West Africa that could ideally be applied regionally, alone or in combination, regardless of country, ethnicity of the coastal community, livelihood activities, type of coast (sandy beaches, mangrove forests, estuaries, coastal lagoons), met-ocean conditions and coastal hazards. This approach is classified within the Integrated Coastal Management approach and would consider only the characteristics of the coast and the people living on it.

The review therefore seeks to develop a compendium of coastal management practices in West Africa. We first describe the geographical environment of the West African coastline, the met-ocean forcing and natural and human hazards. Secondly, the authors introduce and review coastal management practices or adaptation responses that currently exist, whether or not they have been applied to West Africa, depending on their nature.

## Study area

The scope of this study includes 14 West African coastal countries: Mauritania, Senegal, Cape Verde, Gambia, Guinea-Bissau, Guinea, Liberia, Côte d'Ivoire, Ghana, Togo, Benin, Nigeria and Sao Tome and Principe. The West African coast, which stretches from Mauritania to Nigeria, including the archipelagos of Sao Tome and Principe and Cape Verde (Fig. 1). The coastline of West Africa that is described here has been categorised into three regions with mostly common geo-environmental properties and met-ocean driving forces:

- The Northwest- from Mauritania to Guinea Bissau,
- The muddy and sandy West coast- Guinea-Bissau to Sierra Leone,
- The Gulf of Guinea- from Liberia to Sao Tome and Principe.

## Geo-environmental characterisation

### Geological characterisation, an evident role of human driven erosion

These 14 countries cover about 6000 km of a dynamic and mostly soft coast, composed of mangrove forests, mud, sandy beaches, sandy spits, rocky beaches and estuaries (Allersma and Tilmans 1993; Anthony 2006; Dada et al. 2020). West Africa presents a rich coastal geomorphic variability from the narrow continental shelf, sandy dune-bound coasts of

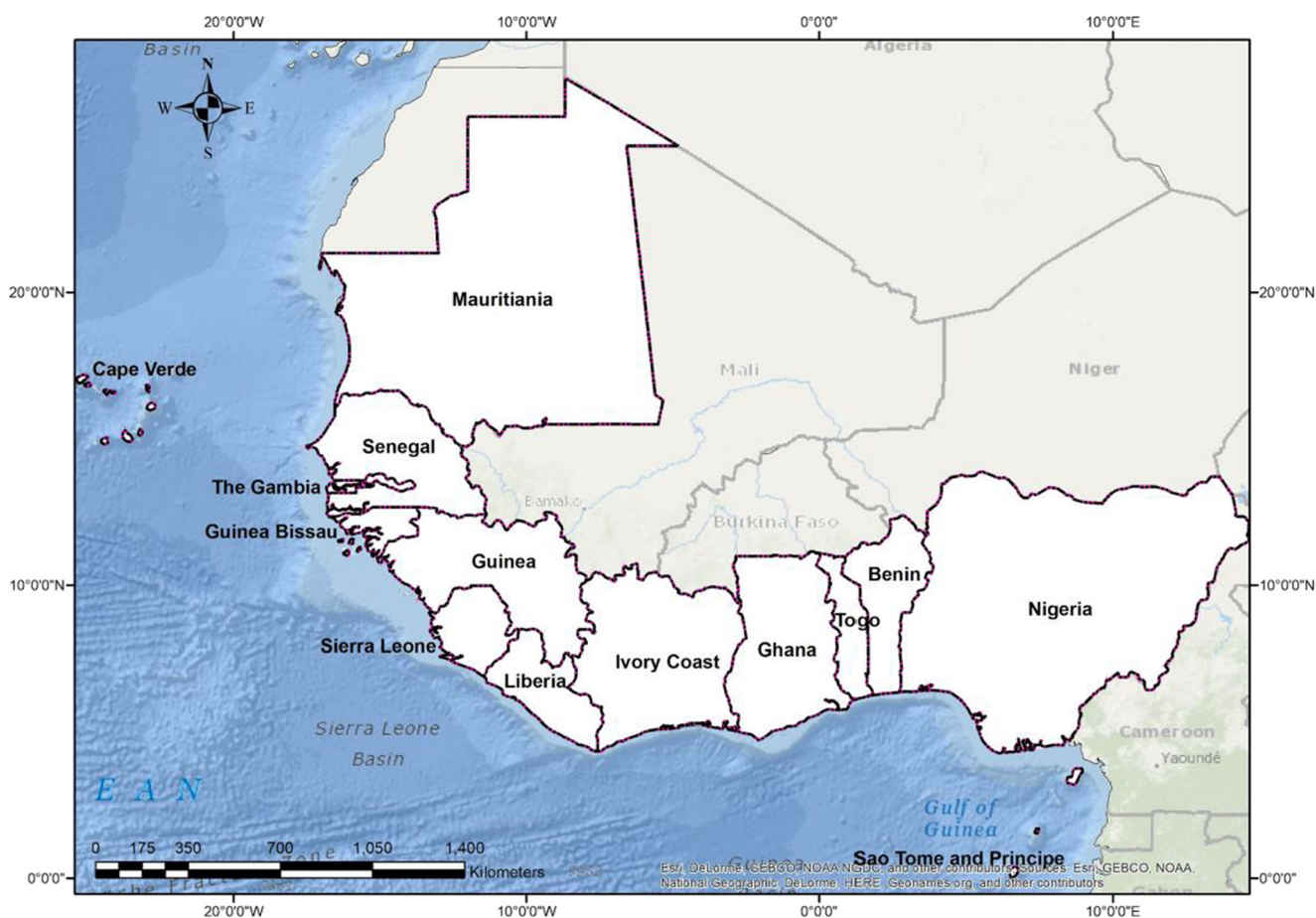


Fig. 1 West Africa coastal countries

Mauritania, Senegal and Gambia, and their commonly narrow spits bounding estuaries (with the exception of the large Gambia River ria and its southern adjacent cliff-bound coast), through the transitional muddy Guinea-Guinea Bissau-northern Sierra Leone sector where cliff-bound coasts and open estuaries rich in seafront mangroves are favoured as a result of strong wave dampening and tidal range amplification generated by the considerable increases in continental shelf width related to geological offsetting of the shelf by the Guinea and Sierra Leone fracture zones, and down once again to the narrow shelf, bounded by massive rectilinear sandy beach-ridge complexes with diverted river systems and back-barrier lagoons from southern Sierra Leone to the Niger delta.

**The northwest- from Mauritania to Guinea Bissau** The coast of Mauritania is mostly flat in the north. It is an enormous, dry plain broken by sporadic ridges and cliff-like outcrops. The coastal area of Mauritania varies between high energy beaches in the north and the mangrove environment at the mouth of the Senegal River. The most exposed area to coastal hazards is Nouakchott, the port constructed in 1986. In Nouakchott, protective structures including a dam that was constructed in 1987 and a groyne built in 1991 to protect the coast have

started to break down. Erosion rates of about 25 m/year have been observed in this area. The coastal areas of Senegal and Gambia encompass a wide variety of coastal ecosystems, including long sandy beaches, some volcanic rocky areas (Cape Verde Peninsula) and especially large areas of estuaries at the mouths of the Senegal, Saloum, Gambia and Casamance Rivers. In the Senegal and Saloum Estuaries there are large spits and barrier beaches. Due to oceanographic and climatic conditions or to anthropogenic actions, these geomorphological sand structures are very mobile and can endanger the inhabited areas (Kane et al. 2013). The Ndiago community around Saint-Louis, Senegal, is at risk (UNESCO-IOC 2012) of erosion. In addition, there are also several wetlands, mangroves and sandy islands in the estuaries, and salinisation affects agriculture in some areas (Faye et al. 2019). Coastal erosion is a general phenomenon that strongly affects the low coasts of Senegal and Gambia. From 1968 to 1986, these coastal areas had been characterised by accretion. The opposite was observed from 1986 to 2004, when a larger recession was recorded. The recession remained as a decisive element of the coast from 2004 to 2017, though at a slower retreat scale (Thior et al. 2019). So, for many years now this region has been facing the decline of the coastline and, accordingly, the

consequences of which remain significant both environmentally and socioeconomically.

**The west coast- Guinea-Bissau to Sierra Leone** The coast from central Sierra Leone to Guinea-Bissau is an example of a mud-dominated coast that supports large areas of mangroves and rice fields where mangroves have been cleared (Anthony 2006). Although this area lacks major rivers, small but numerous estuaries guarantee a sediment load that increases water turbidity leading to shoreline accretion in certain areas (Anthony 1995, 2006). This muddy coast contrasts with the sandy beaches of West Africa. The Cape Verde archipelago, from a geological point of view, is mainly composed of igneous rocks, with volcanic structures. On the coastlines of Cape Verde, though erosion probably affects a number of islands, there is no information on the intensity of the erosion rates (UNESCO-IOC 2012). The Liberian coast is low lying with a number of deposition and erosion characteristics, such as sandy beaches, lagoons, estuaries, mangroves, rocky bottoms (Ssentongo 1987).

#### **The gulf of Guinea- from Liberia to Sao Tome and Principe**

The coastline of Côte d'Ivoire presents two different typologies. From Cape Palmas to Fresco, the coastal strip is rocky, while from Fresco to the Ghanaian border, the coast associated with a sinking area, is low lying with respect to the 100-m contour, it is sandy and surrounded by lagoons. The continental shelf of Côte d'Ivoire is narrow, about 20–25 km. There exists a submarine canyon off Canal de Vridi, also known as “Trou Sans Fond” (Allersma and Tilmans 1993; Giardino et al. 2018). The coastline of Côte d'Ivoire is also characterised by steep coast, rocky outcrops and pocket beaches. Ghana's coastline is reported as 540 km (Boateng 2012). Using the morphological features of the coast, it has been subdivided into 3 main sectors. These include the Eastern, Central and Western coastal areas. The East coast, nearly 149 km, is the coastal area between Aflao at the border of Togo and Prampram. The East coast is sandy predominantly with barrier lagoons and spits (Angnuureng et al. 2013). The sediment particle sizes range from medium to coarse. The Central coast is categorised by moderate energy. It is a pocket coast of rocky headlands, sandbars and spits enclosing coastal lagoons (Angnuureng et al. 2020). This coast is in embayed contour, with rocky headlands, sandbars and spits that are bordered by sporadic coastal lagoons. The Central coast is more developed than the other areas. It is long, about 296 km, extending from Prampram to Cape Three Points. The sandy shorelines along the coast lie mostly amongst rocky headlands and other promontories. The West coast is only 95 km of coastline from the estuary of the Ankobra River to the border with Côte D'Ivoire. The West coast comprises flat but wide beaches bordered by lagoons and characterised by low energy events. Coastal erosion occurs to varying extent

along the entire coastline of Ghana (Blivi et al. 2002). The coastlines of Togo and Benin lie at the centre of a continuous and uniform system of dune ridges and lagoons in the Bight of Benin which extend - from west to east - from the Volta River Delta in Ghana to the western side of the Niger River Delta in Nigeria (Blivi 1993). The Bight of Benin coast represents one of the longest systems of beach-ridge barrier-lagoons in the globe. This coastal system expands mostly uninterrupted across several estuarine re-entrants over nearly 300 km along eastern Ghana to western Nigeria (Boateng 2012). Until recently, the sandy beaches of Togo and Benin were mainly fed by sedimentary inputs from the Volta and Mono Rivers, which were then redistributed through a powerful west-east coastal drift (Rossi 1989). From the 1960's onwards, the balance of this coastal geological system was totally disrupted as a result of anthropic actions (Ozer et al. 2017). Sediment budget have considerably changed due to the fluvial sediment inputs being reduced following the construction of dams on the two main rivers feeding the coast (Mono and Volta Rivers) and the development of ports and harbours in Cotonou and Lomé that changed the coastal sediment transport (Ozer et al. 2017). Only 34% of the Togo and Benin coastlines is stable. Accretion is observed only in updrift of the harbour infrastructures. Other stretches of coastline undergo erosive processes (52%), sometimes exceeding annual average retreats of 10 m/year. In such conditions, villages have disappeared during the past decade and a large number of people have been displaced (Ozer et al. 2017). Benin consists of low-slope sandy beaches with marshes and shallow lagoons. The areas to the west include the Grand Popo lagoon, separated by only a few dozen meters from the ocean and therefore one of the hot spots of erosion (Boateng 2012). The coastal area around Cotonou reflects the predominant sand movement from west to east, visibly creating sand accumulation west of the port and erosion to the east (Almar et al. 2015). The city of Cotonou itself is very prone to flooding due to poor drainage and land subsidence. The loss of natural habitat on the coast leads to a loss of biodiversity and natural services such as wetlands for flood control, recreation and tourism areas or, in the case of mangroves, protection against coastal erosion. The littoral area of Nigeria comprises 4 different geomorphological components with about 853 km coastline; the barrier-lagoon complex, the mud coast, the Arcuate Niger Delta and the Strand Coast (Ibe 1988; Dada et al. 2020). The arcuate Niger Delta is one of the largest (about 284 km) arcuate fan-shaped river deltas in the world. It is situated south of Nigeria, along the Gulf of Guinea coast from the West of the Ramos River entrance to the East of Sombreiro River entrance. Since 1956 there has been an increase in oil exploitation in the area, especially in the villages of the Niger River Delta. This coastal area is low-lying, with elevations limited to 3.0 m above sea level. The coast is largely covered with freshwater swamps, mangroves, lagoons, tidal channels, beach ridges and sand bars. Sao Tome and Principe

consists of an archipelago with two main islands; the island of Sao Tome and the island of Principe. The coastal zone includes the slopes of extinct volcanoes, within which the environment is under pressure from soil degradation and coastal erosion.

### Meteo-oceanographic drivers

**The northwest swell**, is oblique to the Senegalese coast and is drifting from north to south throughout the year (Faye 2010a, b; Sadio et al. 2017; Thior et al. 2019). Its oblique direction from north to south causes, on the southern coasts, the formation of coastal spits and sandy ridges extended towards the south. Within the northwest coast, particularly in Senegal, hindcast wave data retrieved from Wave Atmospheric Model and the European Re-Analysis from 1984 to 2015 reveals that the wave regime is a mixture of swell and wind waves (Sadio et al. 2017; Ndour et al. 2017). Calculation of the average for the period 1984–2015 (using Era-Interim - a global atmospheric reanalysis available from 1 January 1979 to 31 August 2019, a product of the European Centre for Medium-Range Weather Forecasts) gives significant annual swells and wind waves of heights (Hs), 1.5 m and 0.5 m, respectively, and maximum peak swell and wind wave periods of 9.2 s and 3.0 s. The main wave direction is from WNW to N (Ndour et al. 2017; Almar et al. 2019). The range of wind wave direction is larger. Its influence is especially noticeable throughout the north direction of sand dunes on the Casamance and Gambian coasts. The wave direction shows momentary oscillation in August dominated by the south swells (Almar et al. 2019). The wind waves show a much wider directional window. There is a clear seasonal modulation, with maximum wave activity during winter in the northern hemisphere, with strong storm activity in high and mid-latitudes. Wind waves also show greater daily and monthly variability. Unlike swell waves, wind waves are carried by local tropical winds and show peaks in spring and autumn that correspond to the passages of the Inter-Tropical Convergence Zone over Senegal. The distant high latitude oblique energy waves cause one of the highest coastal drifts in the world (~800,000 m<sup>3</sup>/year in Saint-Louis, Sadio et al. 2017). The tidal regime is mostly semi-diurnal and the amplitude of the tides varies from 0.5 m at neap tides to 1.6 m at spring tide.

**The west coast** The muddy coast from Sierra Leone to Guinea-Bissau is oriented SE-NW (Anthony 1989, 2004, 2006). This coastal area is a major junction coast in terms of the wave climate in the region (Anthony 2006). It is exposed to swell waves from the North and South Atlantic. This coast experiences northwest waves that are of low to moderate energy, with offshore water heights less than 1.2 m for about 70% of the time and southwest waves of heights between 1 and 3 m. The wave climate comprises annual dominant long

period swells ( $T = 8\text{--}16$  s) and mixed with seas ( $T = 7\text{--}5$  s) from the northwest, and mixed swells and trade-wind waves ( $T = 8\text{--}12$  s) from the southwest, that are periodically dominant between June and October (Anthony 2006). Maximum Hs during the higher-energy season of south westerly waves do not exceed 1 m. The tides in the area semi-diurnal with meso-macrotidal range (with mean tidal range of 3–5 m) which shows a south-north increase hinged on the width and geometry of the shelf.

**The Gulf of Guinea** This coast includes Liberia, Côte d'Ivoire, Nigeria, Ghana, Benin, Togo to Sao Tome and Principe, and stretches over 2000 km between 7°30' W and 9° E. The Gulf of Guinea coast also comprises the Bight of Benin between Ghana and Nigeria (Laïbi et al. 2014; Almar et al. 2014, 2015). The Gulf of Guinea coastal wave climate is therefore characterised by two very contrasting components: locally generated wind waves and a dominant component of long, medium- to high-latitude swells. The Bight of Benin is an open environment exposed to long swell waves travelling from the mid to high latitudes (45° - 60°) in the South Atlantic, as well as locally generated short waves in the tropical band (6°N - 15°S) to the coast. The swell waves are more conspicuous during the rainy season (June to September), with an extensive dispersal of sediment towards the coast. The mid to high latitude wind regime is characterised by strong westerly winds, while the subtropical zone (30°S - 35°S) is dominated by south easterly trade winds blowing off the coast of Namibia (Almar et al. 2015). South-westerly swells are slightly oblique at angles of 10°-15° on the Bight of Benin coast. The tidal regime is microtidal, with 0.3 m and 1.8 m for the neap and spring tide ranges, respectively.

Generally, the entire West African coastal area of concern is cyclone and storm free, even though swells from distant tropical cyclones can hit the coast (Almar et al. 2019).

### Socio-economic context

The human footprint in the study area is dominated by the concentration of population and economic interests. The UN-Habitat (2014) reports that over 25% of people in West Africa reside around 100 km from the coastline. It also reports that over 50% the total population staying in low-lying areas is urban. The population has grown rapidly at an average annual rate of 2.75%. It has also become more urban, with some large cities recording mean annual growth rates of up to 9% (CILSS 2016). The coastal zone is strategic as it concentrates modern activities but remains marked by contrasts. Most of it is uninhabited mangrove or desert, as most of the population still lives in rural areas, small villages and fishing communities (CILSS 2016). However, some stretches of the coast are marked by large cities, ports and other economic interests (Ndour et al. 2017) which increases the risk of exposure

(UN-DESA 2018; Glasser and Farvacque-Vitkovic 2008). The population of West Africa is unevenly distributed and clustered along the coasts. It is evident that the population is not consistently distributed even when it is close to these environmental amenities. The West African coast emerges as a large area of high-density settlement, stretching from Port Harcourt (Nigeria) along the coast, through Lagos (Nigeria) and Accra (Ghana) to Cotonou (Benin) and Abidjan (Côte d'Ivoire), before declining in density towards Liberia (Glasser and Farvacque-Vitkovic 2008). Larger cities are almost merging. For example, the coastal area from Accra to the Niger Delta is prone to being a continuous urban megalopolis, with over 50 million population dwelling along the 500 km of coastline (Post and Lundin 1996).

### Human-induced pressures

Urbanisation along the coastline of West Africa has augmented pressures on coastal and marine ecosystems to worrying levels. This is more particular in areas such as Côte d'Ivoire, Ghana and Nigeria, where the coastal areas are home to most of the industrial activities ranging from textile, leather, food and beverage processing industries to oil, natural gas and mineral industries (World Bank 1996). In addition, the key river basins such as those in the Gambia, Nigeria and Senegal as well as its biodiversity of global importance are seriously threatened by ecosystem degradation. Land use, development due to rural urban migration, population changes and growth, poverty and absence of alternative livelihoods, increasing consumption rates (e.g., building materials, fish) all increase the demand for coastal and marine resources (Celliers and Ntombela 2015). According to the UN-Environment Programme/Nairobi Convention Secretariat, there are some links between urbanisation and coastal environmental quality that include degradation of water quality, modification of habitats and communities, and overexploitation and decline in living marine resources. Suitable planning for population growth is critical in the coastal zone to ensure the reduction in poverty and sustainable development.

### Coastal management practices already applied in West Africa

Herein we examine aspects of coastal management practices that exist in the West African sub-region (Fig. 2). It is difficult to have a comprehensive of all cases and we generally focus on a few to illustrate the benefits and issues encountered. To the authors best knowledge, in the coastal areas of West Africa, there is no literature on adaptation responses that can be classified as a nature-based solution for coastal management.

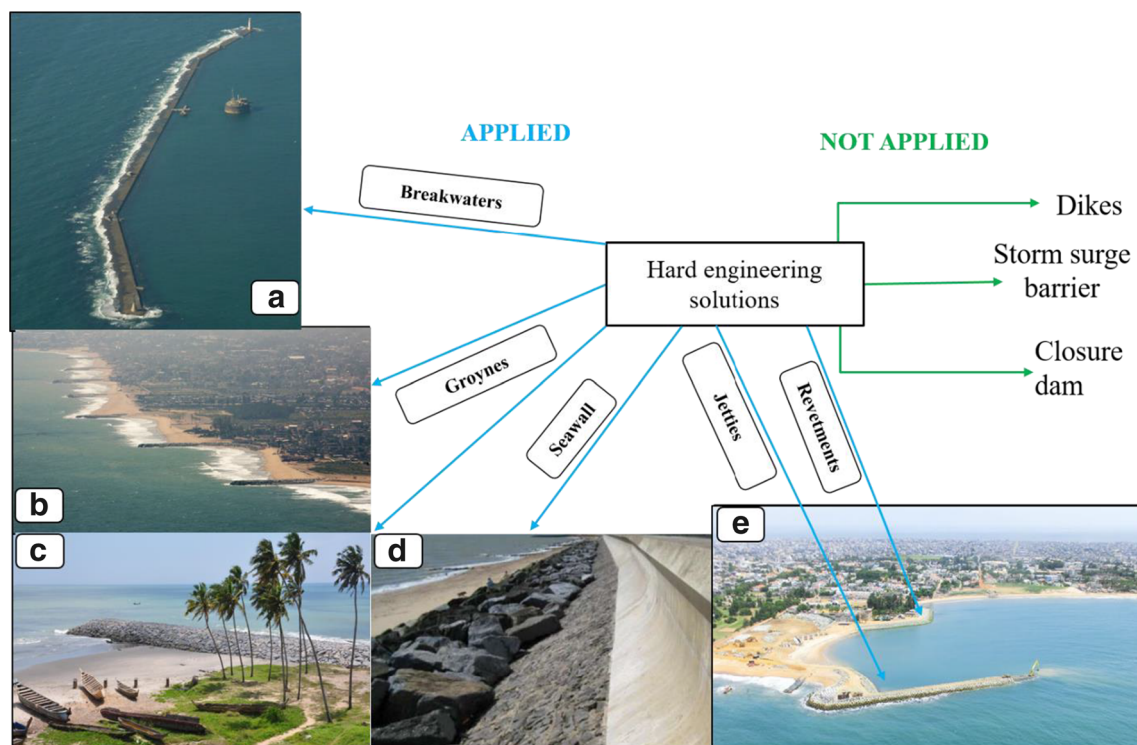
## Hard engineering solutions

### Breakwaters

Breakwaters are offshore structures designed to intercept and reduce wave impact arriving at the coast. In West Africa, breakwaters are mostly implemented at the harbours for the purpose of reducing wave actions on ships. For instance, the deep water port of Lomé opened in 1967 and the distant Akosombo Dam in Ghana have played a great role in disrupting the sediment dynamic along the western coast in the Bight of Benin (Anthony and Blivi 1999). Togo faced several coastal management challenges that involved shoreline dynamics, pollution, flooding, and the possible effects of rising sea levels. The Lomé beach eroded at an average rate of nearly 7 m/year (Blivi 1993). To control this, the coastline was protected by building breakwaters along 12 km of the coast from Kpeme Gumukope to Aneho (Blivi 1993). Furthermore, as part of the Benin Sea Defence Project to protect 7 km of coastline that was eroded to 762 m in 40 years, a 300 m long breakwater was constructed. Other breakwater projects implemented in West Africa include the Abidjan Port Expansion Project. The construction includes the demolition and reconstruction of the east and west breakwaters at the entrance to the canal. The project aimed to improve the status of the port of Abidjan as a central port on the Atlantic coast and to promote socio-economic development of Côte d'Ivoire and West Africa as a whole.

### Groynes

The use of groynes to mitigate, or displace, coastal erosion facing urban or punctual important (important enough to be protected) areas, is the most popular method practiced in the West African sub-region, from Senegal to Nigeria. The Keta coastal area which is located east of the Volta River estuary started experiencing erosion between 1870 and 1880 after about 200 m to 300 m of land was removed from the central Keta area (UNESCO-IOC 2012). The recession at the mouth of the Volta grew annually at between 4 m and 10 m after the Akosombo Dam was constructed on the Volta River (Angnuureng et al. 2013). This dam prevented about 99.5% of sediment discharged by the river from getting to the beach (Ly 1980). Since the construction of the dam, most of the protection methods that have been implemented to stabilise the coast have not produced the needed outcomes. In 1955–1956, a steel wall made of sheet piles was constructed, but this broke down in the 1960's. Between 1976 and 1978, short-term methods such as using revetments to protect the Fort in Keta, proved futile because there was no filter material under the groynes. Majority of the rocks sank into the sandy sediment. Following many investigations at Keta on the coastal erosion, the Government later built 7 riprap groynes to help



**Fig. 2** Examples of hard engineering techniques applied along the West African coastline. Examples (a), (b) and (e) are implemented at Cotonou Port. Example (c) is a groyne at Elmina Beach, Ghana. Example (d) is a seawall at the coast of Keta, Ghana

stabilise about 7.5 km stretch of this coast. Since the completion of the project, the coastal section has been stabilised and secured along a 7.5 km coastline. This has enabled the establishment of other structures, for example, social services were created for the communities that were highly vulnerable to extreme events. The defence improved sediment accumulation on the updrift of the coast. However, the construction of the Keta sea defence with combined breakwaters and revetments, has resulted in an increase in coastal erosion along the coast downdrift the Ghana/Togo border of more than 50%, i.e. Keta sea defence became the major cause of increased erosion (Angnuureng et al. 2013). Despite this and because various parts along the Ghanaian coastline are eroding, the government is carrying out several major sea defence projects in sites considered to be very susceptible. These include the Ada sea defence, Sakumono sea defence, New Takoradi sea defence and Elmina sea defence projects, which extend along the coast of Ghana. However, these site-specific interventions show an impact on most of the adjacent beaches.

This type of coastal erosion control measure is being implemented along other coastal areas in West Africa. For example, the Cotonou erosion control project was designed with the hope of replicating it in other West and Central African (UNESCO-IOC 2012) countries. The sea defence on the coast of Cotonou, Benin, was constructed with five short low-lying groyne. The aim was to stabilise the coastline in front of the new residential area that was suffering from a sharp reduction

in coastline at a rate of 2–3 m/year. In 1988, the coastline had advanced by about 650 m at the western edge of the Port, while at the eastern edge of the Port, the shoreline retreated by about 500 m within the same time. The setback of this project was that it could not be completed according to specifications due to cost. There was no site monitoring as required to adapt to designed parameters and, if feasible, make the necessary adjustments. The project was finally abandoned due to cost, the lack of routine maintenance and the fact that it was partially completed.

### Jetties

Jetties ensure reliable stabilisation of tidal inlets or river mouths, regulating the development of undesirable features, like channel siltation. These structures are usually constructed to intercept sediment that is transported alongshore, so that they can prevent sediment accretion in inlets or estuaries. Large quantities of sediment are trapped in the updrift of the jetty. But such a process also results in a narrowing of the coastline downdrift of the jetty. Since jetties are relatively longer than groyne, greater sediment loss to deep water is much more experienced during storm events (Masselink and Hughes 2003). Jetties are, for example, located at the eroding tidal inlets of the Elmina Benya lagoon in Ghana, in the port of Takoradi, in the port of Cotonou as well as in other areas along



the Gulf of Benin (Anthony et al. 2019; Abessolo Ondoia et al. 2020).

### Revetments

Revetments are structures to protect a soft feature such as a dune or coastal slope or provide supplementary protection to existing defences such as a dike or seawall (Bayle et al. 2020). Between 1959 and 1960, a 100 m long revetment was built on the coastline of Jamestown, Accra (UNESCO-IOC 2012). This was a measure to counter coastal erosion after the Korle Lagoon landfill site was constructed. After 15 years, sea waves ravaged the revetment structure. A road located east of the structure was also affected by overtopping sea waves. The overtopping, mostly at high tide, led to a break in the road between Korle Lagoon and Accra Central. To prevent this breakage, a revetment approach was implemented between 1983 and 1984. Within 12 to 18 months, the waves overtopping the road had stopped; there was a considerable accumulation of sand and the profiles of the beaches became gentler. The revetments were built to a flat gradient leading to essential dissipation features of the rock-filled gabions and the main reason responsible for the high accretion.

Another remarkable experience with revetment implementation has been observed at Labadi beach in Accra (UNESCO-IOC 2012). Here, the recession rate of the coast ranged from 3 to 5 m/year for 1955–1985. The 1965–1978 period recorded the highest recession rate. During this period, about 100 m of beach, earmarked for the creation of leisure projects, underwent erosion at a rate of 7.5 m/year and caused the development of the project to be stopped. In 1982, a revetment was constructed with box-filled rocks. This was the first time gabions were used as a measure to solve coastal erosion problems in Ghana. The shoreline protection project of Labadi, including a 1600 m shoreline, was organised in 3 stages that progressively led to the mastery of the technique. Once the construction of the revetment structure was completed, the beach was protected from wave attack; the underwater beach profile flattened and a sense of security developed.

### Seawalls

A seawall can be described as a type of coastal defence built where the sea, and related coastal processes, influence directly the landforms of the coast. The advantage of an efficient seawall incorporates its ability to provide a higher level protection during coastal flooding or recession. If properly designed and maintained, it serves as the margin between the land and the sea, while ensuring that no erosion occurs further. In addition, seawalls do not take up much space, especially if vertical seawalls are designed, which reduces the cost of construction.

Seawalls are used in several parts of West Africa. Examples include Rufisque, a coastal community in Senegal. Two types of dikes have been constructed in Keuri Kad and Keuri Souf. These walls were built between 1983 and 1990 and have a total length of 3.5 km. Recent assessment has revealed that some sections of these walls have collapsed because they were so fragile, poorly applied and could not prevent high waves from breaking. Aside this seawall, between 1990 and 1992, concrete walls were built in Diokoul (Senegal) on gabions (UNESCO/IOC 2012). These walls are also currently in a state of failure or collapse. However, this solution is continuously being used as a new seawall was constructed before the collapse of the first wall (UNESCO/IOC 2012). In Ghana on the Gulf of Guinea coast, this approach has also been used. A steel sheet piling seawall was being constructed in Keta (Ghana) around 1955–1956 period but this activity stopped in 1960 because of persistent coastal erosion. The seawall collapsed rapidly and shortly thereafter. So currently, the use of seawalls for coastal erosion prevention is done in integration with groynes and gabions. This has resulted in the stability of the seawalls as well as preventing waves overtopping.

## Soft engineering solutions

### Beach nourishment

Beach nourishment has been practiced along some coastal sections in West Africa. For example, at the bar beach on Victoria Island in Lagos and on the beaches of Kololi in Gambia. Victoria Island's barred beach in Lagos is located on the eastern pier that runs down the entrance of Lagos harbour (Awosika et al. 1993; Folorunsho 2004; UNESCO-IOC 2012). To evade the imminent destruction of human settlements, offices and interruption of socio-economic activities on the Island of Lagos, artificial nourishment of the beach was done until a sustainable solution was discovered. The artificial nourishment of this beach was scheduled at 2–3 year intervals, making this solution a very expensive option in the long-term. The artificial replenishment of Lagos Beach failed due to the need to continuously feed the beach as scheduled for the stabilisation of the rapidly eroding beach. In Gambia, there have been several other beach nourishments on the beaches of Banjul and Kololi (UNESCO-IOC 2012). Despite the nourishment, Banjul beach eroded to a length of 68 m in 7 years and 134 m at the Kololi bar sea view point. The Government of Gambia had invested some US\$ 20 million in artificial nourishment of a beach of about 100 m wide in Kololi (Bromfield 2006; UNESCO-IOC 2012). Gambia chose this technique to preserve the aesthetic nature of the beach. It was however noted that this alternative showed the loss of half of the introduced sand within 2 years (Bromfield 2006; UNESCO-IOC 2012).

## Natural areas (dune and mangrove) restoration

Dune rehabilitation is the restoration of natural or artificial dunes to obtain benefits from coastal protection. In West Africa, only Nouakchott in Mauritania, has this practice been documented in the framework of a project for sand dune fixation (FAO 2010). The project which was initiated in 2000 was completed in 2007. Before this, eight hundred hectares of stabilised and fixed inland dunes had been used to improve reforestation from 1987 to 1992. The Mauritania project effectively resulted in the stabilisation of 50 ha of dune ridge in Nouakchott with sand capture and reforestation (UNESCO-IOC 2012). One mechanically stabilised and biologically fixed hectare cost about US\$ 4184 covering approximately 600 linear metres. Therefore, one linear metre of mechanical dune stabilisation costs up to US\$ 6.97, which implies that the method could be costly for most West African countries and therefore cannot be replicated in most areas.

Similarly, to natural beaches and dunes, that provide an ecosystemic natural protection when they are fully preserved or maintained, wetlands are an important buffer area. Wetland denotes various ranges of shallow and intertidal water habitations found in several parts of the world. For example, Ghana's 550 km of coastline includes more than 100 estuaries and lagoons, but these valuable natural resources are threatened by human behaviour and natural processes.

Wetland restoration could potentially decrease the rate at which wetlands are disappearing due to developments along the coast of West Africa. Mangrove forests within West Africa cover huge areas and include six species. The common species are *Rhizophora* and *Avicennia*. In 2008, a total area of 1.5 ha was replanted with *Rhizophora* mangroves (UNESCO-IOC 2012) on Djirnda Island of Saloum in Senegal. The cost of mobilising and caring for 100 people for one day of reforestation was estimated between US\$333 and US\$450 (UNESCO-IOC 2012). There was also reforestation at Gagué Sharif in Sine (Senegal). However, due to the high salinity of the soil the results can be disappointing. Mortality was high and the growth of survivors was slowed down. In spite of the modest size of the reforested area, this action has a considerable impact on the motivation of people involved in restoration and is relatively cheap to carry on.

## Coastal planning techniques for risk mitigation

### Early warning systems

In the coastal cities of West Africa, the system of early warning has not been implemented adequately in relation to flood damage reduction. Flood warning systems are sporadically

implemented in West Africa; only in Cotonou (Benin) and Dakar (Senegal). In Accra (Ghana) and Lagos (Nigeria), these warning systems are applied but they do not function properly as proven by the loss of 200 lives in floods that occurred in June 2015 in Accra (IFRC 2015) and 2012 in Lagos (IFRC 2012). The development of early warning systems in most countries has been carried out in the framework of projects funded mainly by bilateral agencies such as UNDP, WMO, etc. Unfortunately, in most cases, after the end of the projects, the systems fail due to lack of maintenance.

### Flood regulation through river regime (and sediment) management

In estuarine/riverine areas, where the flood risk depends mainly on the river flow, flood risk reduction is required in the hydrological settings of the river through regulatory infrastructures (e.g. dams). Indeed, dams regulate river water flow, and the management of water relies on the decisions of the community people. For example, in the case of the Saint-Louis, many issues arise with the management of the Senegal river (Dumas et al. 2010). However, the priorities in management of two dams on this river were principally oriented towards the development of irrigated crops on floodplains and the production of electricity (Manantali Dam). It is reported that the authorities around the river intended to maintain the high water levels inside the Manantali reservoir as long as achievable. This was not succeeded based on the plan by management to control floods downstream of Diama. The city of Saint-Louis got inundated in September 2003 since Manantali Dam could control only a section of the river basin. The dams could not prevent or control the flooding. In addition, a second flood that was supposed to arrive in the city 20 days later occurred simultaneously upstream of Bakel and aggravated the impacts of the first flood. At that time, Saint-Louis was about 30 km from the river mouth and was disconnected by a long coastal spit (Langue de Barbarie) away from the ocean. To permit the river drainage and reduce the distance between the city and the river mouth, an opening was dug in Langue de Barbarie as an emergency response, which is about 7000 m downstream to Saint-Louis. This followed an instantaneous decrease in flooding. The modification of all the discharge from the river by the dams and embankments, and more recently when the Langue de Barbarie was opened, yielded to extreme alterations in the flow of the river and rapid adjustments to the environment. This led to sudden impacts on the environment, mostly due to the initial uncertainties about the water system and its management. Dumas et al. (2010) showed the unexpected dynamics caused by the artificial transformation of the valley, which is far from the development of any capacity to protect the population from flood peaks.

## Flood mapping

Several countries are highly exposed to the effects of flooding hazards because there is insufficient investment in infrastructure (Ntajal et al. 2017), economic dependence on agriculture, buildings in flood prone areas and scarce resources for institutions. Consequently, flood mapping is an important process in sub-Saharan African countries, with various approaches in each country.

Floods reoccur every year in several areas in West Africa. Every year, the Togo government uses the services of its institutions including the Ministry of Environment, Territorial Administration, Civil Protection and the Red Cross (Ntajal et al. 2017) in flood mapping activities at the Mono River basin to save lives and property. The evaluation and mapping the risks of flood in the lower Mono River using a risk map indicated that all communities were at risk of flooding, particularly Agbanakin, Azime Dossou and Togbavi, had relatively high levels of flood risk. A constructive approach as action and to early warning systems, cooperation between disaster relief organisations and appropriate building codes is recommended to reduce the risk of flood disasters.

It remains a huge debate as to the real causes of flood disasters in most cities of West Africa. In Accra floods remain as a major factor in human vulnerability (Amoako and Boamah 2015) over the years. Amoako and Boamah (2015) provide details about the various causes of floods so that an integrated approach to flood management can be established. Based on mixed methods which integrated document reviews, consultations from institutions and interviews of key informants, the study organised the causes of flood hazards in Accra into 3 general but interrelated thematic areas (physical, social and political conditions) that required a platform for integrated flood management.

Today, West Africa flood victims anticipate reliefs. There is no information from international organisations and civil society leaders about programmes to regulate future floods. Consequently, flood-prone areas in other parts of West Africa need to be more adequately and systematically studied and mapped for more effective disaster risk reduction and climate change adaptation.

## Managed relocation

In most cases, the planned relocation operations in West Africa are recent because they are linked to the current context, which is characterised by both high human densification on the coast and accelerated coastal retreat. However, Grand-Lahou, on the coast of Côte d'Ivoire, experienced a major relocation operation. This city, the country's second port from 1910 to 1934, was relocated in 1975, following a government decision that drew the consequences of a long period of damage caused by the sea, which had begun in the 1920's. The

particular situation of this city, on a sandy barrier beach at the mouth of the Bandama River, is at the origin of its great vulnerability. Therefore, all the modern buildings and administrative services of this important city have been moved inland, at a distance of 15 km. The operation was not a complete success because the populations dependent on marine resources preferred to remain on the barrier beach to continue their traditional activities (fishing). Now they suffer from a total lack of fresh water and are increasingly threatened by erosion, being forced to move part of their homes every year. A new project is trying to find a solution for these fishing communities.

In 2012, Côte d'Ivoire took preventive measures by ordering 6000 families in the flood-prone areas of Abidjan to relocate with every US\$300 they were given to do so. The relocation helped to save lives. According to Fiacre Kili, director of the national civil protection office, "previous rainy seasons have caused deaths in some districts due to landslides, rock falls and floods".

## Coastal management practices to be considered for West Africa

In this section, we discuss individual aspects of coastal management practices that do not currently exist in the West African sub-region (Fig. 3) and could be applied in the future.

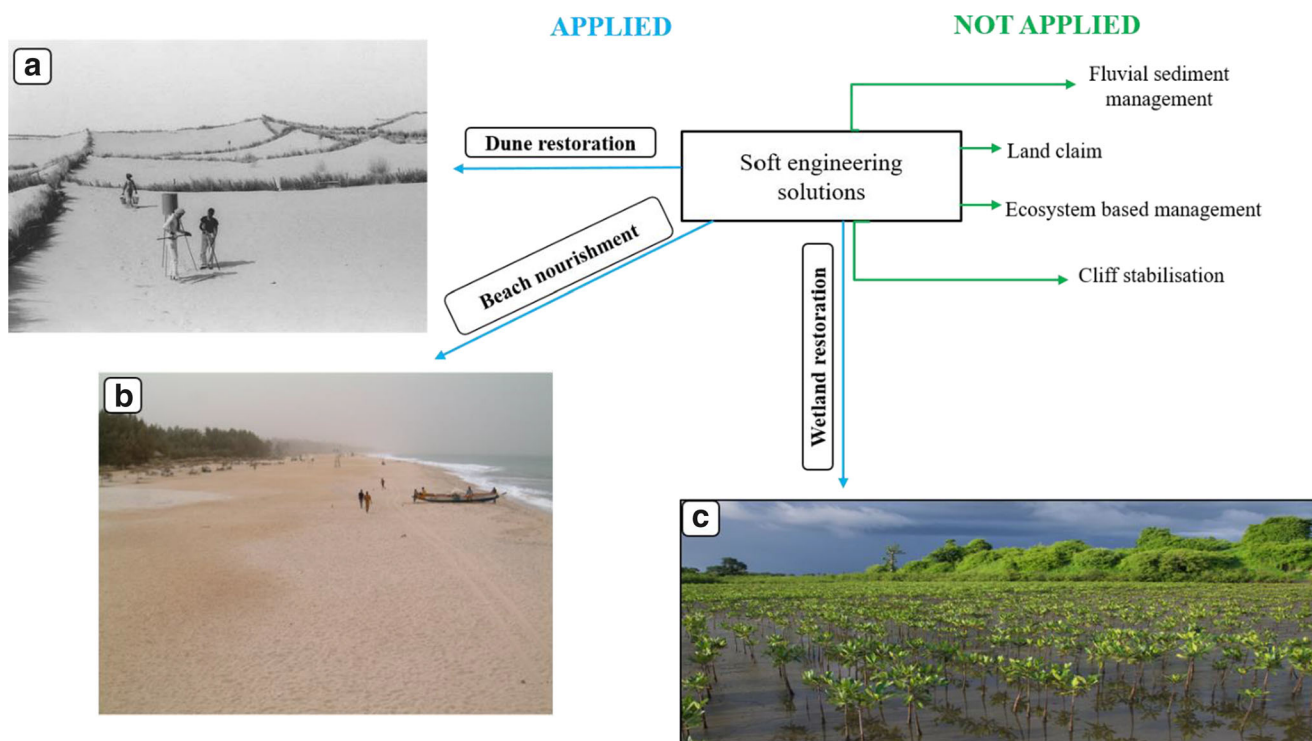
### Soft engineering solutions

#### Land claim

Land claim is a more rigorous way of coastal protection that can be accurately referred to as "attack" or "advance the line" in terms of shoreline management. The principal aim of land reclamation is neither erosion nor storm reduction, but to create new land from areas previously under high tide for agricultural or development purposes (Appelquist et al. 2016). Considering the high enforcement values and negative aspects associated with this practice (contaminated dredged sediment), especially if the new land is to be used for agriculture or where coastal waters are important for fishing, land reclamation may not be the ideal practice to be considered as a coastal management option in West Africa, where many activities still depend on agriculture and fishing.

#### Cliff stabilisation

The coastal area of West Africa is not only diverse and extensive because of its wide sandy beaches to dense mangrove forests, but also because of rocky cliffs, such as the cliffs of Mauritania and the rocky promontories of Ghana.



**Fig. 3** Examples of soft engineering techniques applied along the West African coastline. **a** is an example of the grid of branch fences created to stabilise the sand dunes in Nouakchott, Mauritania. **b** is an example of

finished nourishment at Kololi Beach, Gambia. **c** is an example of mangrove restoration in Casamance, Senegal

Cliff stabilisation is principally important on exposed soft rock coasts (Appelquist et al. 2016). These land formations are vulnerable to coastal erosion because of their comparatively unconsolidated sediment particles that are susceptible to attack by erosive forces like near-shore waves, winds, tides, currents, storm surges and sea level rise. The practice relates to measures taken to minimise the erosion of soft rock slopes and thereby stabilise the coastline. It is a form of soft engineering - this method is often a more sustainable and sometimes cheaper approach to coastal defences, using natural processes to protect the coast against flooding and erosion. Considering the implementation costs and the few cheap alternatives mentioned above, the stabilisation of the cliffs along the West African coast (where this geological feature is present) may be another coastal management practice to be considered for application over a long stretch of coastline.

## Hard engineering solutions

### Dikes

Dikes are applied in low-lying areas prone to floods caused by the sea water mostly during extreme wave conditions. They are not intended to preserve beaches that may occur in front of the structure or any adjacent, unprotected beach. There are several low-lying areas along the coast of West Africa where the construction of dikes could be of great help in protecting

the interior and the population. However, once again, it is imperative that the economic viability of not only building but also maintaining such expensive coastal engineering practice be analysed.

### Storm surge barrier/closure dam

These coastal defence structures are structures capable of protecting tidal inflows, rivers and estuaries from intermittent storm surge occurrences (Appelquist et al. 2016). The main demerit of the storm surge barrier is that it is capital intensive with high maintenance costs. As this coastal management solution involves high capital costs for implementation and maintenance, it is not well suited to the general situation in West Africa, unless it can be considered in the future for very specific areas (e.g., estuaries bordered by large cities).

## Coastal planning techniques

### Non-intervention/do nothing

Doing nothing is an easy coastal management option. It is about the effects of flooding and erosion as they occur or simply ignoring them. This is generally the case in areas where there are no people, so nothing of economic or institutional value should be protected. Today there is a practice of non-intervention/no action in West Africa, but this is not an

act of addressing coastal problems in a planned manner. Many sections of the West African coast are under natural and man-made threat without any coastal management plan in place. This is not what the “do nothing” approach preaches: dealing with natural phenomena, possibly losing land to the sea, but without loss of infrastructure or even lives. While this is obviously the cheapest and most environmentally friendly option for many parts of developing regions such as West Africa, one must weigh the costs (for people, tourism, industries, infrastructure) against the benefits (the advantages of letting the area return to its natural processes). If the costs greatly outweigh the benefits, for example by having to relocate people or losing valuable facilities, then other options must be considered. This is not practiced in West Africa. Not all problems have been addressed because there are no financial resources for governments to conduct detailed research. Otherwise, they would surely do something. It is therefore advisable to consider this practice. Do due diligence, and choose to do nothing.

### Groundwater management

The management of groundwater involves both monitoring and assessment of groundwater conditions and direct interventions. Proactive management has great benefits; it helps to continuous supply of groundwater for fundamental human needs. If planning authorities are coerced to think long-term, it will help to ensure consistency of supply, quality, across a range of climate scenarios, and taking into account future hydrological changes.

For example, preliminary groundwater samples from coastal wells along the Dzita coastline in Ghana indicate significant saltwater intrusion leading to contamination of drinking and agricultural water. It indicates that salt water is pushing inland, mixing with and progressively replacing fresh groundwater. This is due to a reduction in the level of groundwater near the coast, probably as a result of excessive pumping of fresh groundwater for irrigation purposes in this coastal community. Groundwater management is commonly considered to be a positive and proactive measure. As such, this approach has few direct disadvantages. However, the full implementation and enforcement of these strategies requires the allocation of significant specific human and financial resources. Groundwater management should be part of integrated water resources management in all national plans in order to avoid such situations. Thus, the groundwater management plan identifies the measures needed to contribute to an effective water management framework.

### Livelihood adaptation

Livelihood adaptations in various forms can reduce flooding. Floating agriculture is a form of using long-term waterlogged

areas for food production. This solution focuses on adapting more regular or prolonged flooding. Although this approach works well in some areas today, it is unclear how sea level and salinisation would influence flooding, which potentially occurs due to climate change scenarios. The system appears to be quite suitable for low-lying areas of West Africa that may be waterlogged for long periods. It would help to empower communities to produce their own products, involving communities in work that can help them become self-sufficient. Another adaptation that could reduce flooding is aquaculture. If instituted appropriately, aquaculture activities could support livelihood while using water-logged areas.

### Coastal setbacks

Coastal setbacks mean giving a marked proximity to a coastal feature like a perpetual vegetation proxy, within which all or certain types of development are prohibited (Cambers 1998). This does not suggest that coastal setbacks will guarantee absolute protection of the coast in question from severe storms, the associated coastal flooding or erosion (Healy and Dean 2000). Furthermore, the distance policies are only set to prolong the life of the established coastal structures. Other policies or management approaches would ultimately be required to preserve important structures if shoreline erosion or sea level rise persist. This approach can certainly be of immense help in preserving the intact and pristine ecosystems still found in the West African region.

### Coastal zoning

Fundamentally, zoning coastal area is a type of land use system for regulating development activities on the coast. This is when the coastal area is divided into designated zones with diverse purposes and restrictions. The zoning requires normally high coordination and public participation levels regulated at distinctive administrative levels. Coastal zoning is a nature and community-based management practice. This approach is appropriate for the region to deal primarily with conflicts in the coastal zone because in West Africa the population, and the stakeholders in general, belong to different ethnic groups, classes and backgrounds. A great effort should be made to overcome this varied perspective of the coastal areas coming from a wide variety of people. In addition, West Africa has yet to invest in institutional capacity, data monitoring and coastal zone knowledge to implement coastal zoning.

### Managed realignment

Managed realignment commonly includes setting back the line of an actively maintained coastal defence to a new line, landward of the original or preferably, to elevated ground. This will augment the creation of intertidal habitat between

the old and new defences. Management realignment is therefore the deliberate process of changing flood defences to allow flooding of a presently defended area (Leggett et al. 2004). A number of terms may be used as an alternative to managed realignment. This approach is appropriate in coastal areas where there is the presence of coastal defences, low-lying land, desire to improve flood or coastal defence systems, sustainability-oriented coastal management attitude, need to create intertidal habitats, and where the society is aware of the benefits of managed realignment. The approach can adequately protect a coastal area or infrastructure from erosion and flood risks (Mcglashan 2003). Nonetheless, it can be expensive, generate high political and social controversy particularly when it involves relocating residents and the confrontation with land owners.

### Flood proofing and sheltering

The basic objective of flood protection is to minimise the impacts of floods on coastal structures (Appelquist et al. 2016). This includes raising structures above floodplains, using plans and construction materials that are more resistant to flood damage, and can prevent flood waters from entering structures on potential flood zones. At the community level, the costs of flood protection to identify properties at risk would normally depend on the number of properties in the flood risk area and related costs, such as flood mapping and modelling exercises.

Firstly, coastal communities in West Africa represent a large percentage of the total population, i.e. flood protection would have to be implemented extensively, which could be very costly. Secondly, West Africa would need to invest seriously in coastal surveillance and numerical modelling so that data and model results could help predict extreme events and flood protection could be a useful coastal management practice.

Flood shelters are elevated and robust structures that can provide shelter to local residents during extreme weather events. Such structures are complemented by flood forecasting and warning systems to enable timely response (Appelquist et al. 2016). The idea of flood shelters in West Africa as a management practice to assist coastal communities does not seem to be the most beneficial because the population living on the coast is huge. For example, Senegal, Gambia and Guinea-Bissau are West African countries where 80–100% of the population lives less than 100 km from the coast (Hewawasam 2002). In addition, a comprehensive early warning system would have to be fully operational to warn the population and evacuate risk areas.

### Flood warning system

Although coastal areas are unequally prone to flooding based on differences in topography and other factors, the

implementation of flood warning systems can provide critical information to protect property and lives. The most operational flood warning system is not only installing meters and telemetry equipment, but to include the use of qualified personnel and carefully designed procedures to warn as early as possible of an impending flood and its properties.

In communities that do not have a flood warning programme but are experiencing floods, and are interested in developing their own, technical support, outreach and education, should be provided to stakeholders and community leaders. A flood warning system does not necessarily is expensive or complicated, the benefits - protection of lives and property - should outweigh any complications or cost. An effective flood warning system requires the continuous compilation of local rainfall data, stream levels and river flows. This could be achieved by systematic monitoring, where active personnel visit stream gages and precipitation measuring sites. Monitoring real time with telemetry systems can also simplify data collection and, in many cases reduce cost, while permitting the quickest possible response to a flood. Therefore, when a warning system is being developed, consideration needs to be paid to 3 fundamental procedures: data collection and processing, the required hardware and software and the way flood warning information is propagated. This planning approach is an easy and feasible method that can be applied in West Africa to ensure the reduction of casualties from coastal disasters.

### Nature-based solutions

Nature-based solutions form an overarching concept that supports and builds on other closely related concepts, such as ecosystem-based management, which is a type of integrated management approach that will be systematically examined in the section “The recent ecosystem-based management approach: The Volta Delta as showcase”.

### Toward more integrated coastal management approaches: Accounting of the complexity of the issues and solutions

In this section, we discuss how solutions and problems have to be better globally considered with a holistic approach for more sustainability. Integrated Coastal Zone Management (ICZM) is not the application of a particular solution. Its purpose is to provide principles to guide the design and implementation of a solution or, in general, a set of solutions to manage or protect a given portion of the coast and shoreline in the most effective and possible way, considering all relevant dimensions and constraints, both human, environmental and economic. The issues to be addressed in integrated coastal management may relate to the following steps to be processed when

implementing a coastal management intervention (Olsen 2003). Implementation begins with the identification of mitigation tools (e.g. coastal management practices such as soft and hard engineering structures, coastal planning, nature-based solutions). Secondly, the selection and evaluation of integrative mitigation strategies. Since mitigation approaches are mostly hybrid, that combine several different measures to maximise benefits while addressing the unique issues of a site, it is binding upon each community to identify alternative actions potentially appropriate to their needs, and to evaluate these strategies in relation to their unique priorities.

Here, we develop two case studies to illustrate the complexity of the problems and the mitigation strategies. They also show that a unique local solution is unlikely to work, and favours a multi- (spatial and temporal) scale and multi solution cooperative solutions, that reflect the dimension and complexity of the issues, environments objects (large sediment cells including input from rivers and coastal redistribution) and human habitats (from traditional communities to dense urban areas) and geopolitical infrastructures (municipalities, regions, states and international cooperation).

### **The recent ecosystem-based management approach: The Volta Delta as showcase**

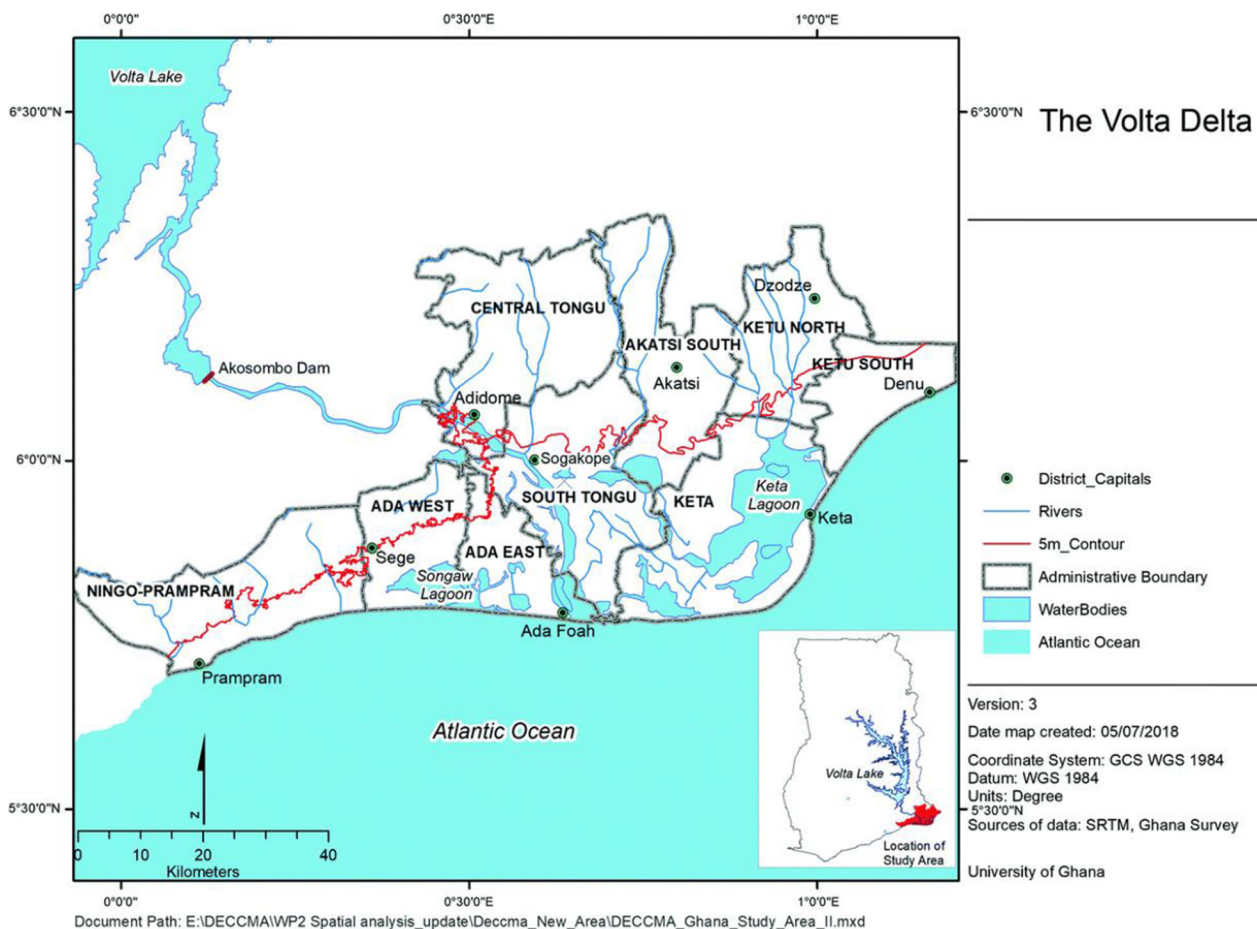
Ecosystem-based management is a general framework that is not dedicated to the coastal domain but can be successfully applied in coastal management. It integrates some of the principles and concerns of ICZM, such as adaptability, multi-sectorality, and a desire to improve the decision-making process. In addition, ICZM deepens and clarifies certain issues, particularly with regard to the recognition of the preservation of ecosystem functions, because it considers that humans are within ecosystems and rather beside them. Thus, ICZM can also be seen as environmentally friendly, which could consist of systematically giving priority to the conservation of ecosystems when making decisions that balance economic and ecological objectives. The objective of ecosystem-based management is to maintain an ecosystem in a healthy, productive and resilient state, so that it can provide the services that humans want and need.

More than 70% of the people of the countries in West Africa within the Gulf of Guinea (Côte d'Ivoire, Ghana, Togo, Benin, and Nigeria) are in the coastal zone, and pressures on the coast are increasing markedly due to continued growth of the main coastal cities. The coastal area of West Africa is obviously influenced by natural factors such as wave climate, geology, topography and shape of the areas. It is also influenced by anthropogenic factors created by the pressures on the coast. The Volta Delta is located in the Keta Basin (Appeaning Addo et al. 2018) between 5°25' and 6°20' N and 0°40' and 1°10' E on the east coast of Ghana. The delta is a land below 5 m contour within the lower portion of the river.

The Volta Delta of Ghana covers a total land area of about 4562 km<sup>2</sup> (Appeaning Addo et al. 2018) (Fig. 4). The delta is fairly uniform with moderately steep shoreface and a gentle slope up to 15-m depth contour. This is believed to be the closure depth where sediment transport on this coast through significant wave action ceases (Anthony 2015). This Delta is dynamic and extremely vulnerable because of flood impacts that result from relative sea level rise, extreme oceanic wave actions, subsidence and anthropogenic impact such as dam construction (Anthony 2015; Appeaning Addo et al. 2018). The complexity of the causes of erosion/flooding (river discharge, human infrastructures and pressure) in the Delta land are prominent. The wave climate in the Delta is similar to that of the Gulf of Guinea region described earlier. The Delta is home to 9 administrative districts which are responsible for managing resources around the Delta. Yet, there is no explicit national policy devoted exclusively to the Volta Delta except formal rules established in the form of laws, policies, protocols and agreements during colonial and post-colonial times to ensure management. The Delta comprises diverse economic structures with dissimilar yet integrated sectors, such as agriculture where livestock rearing, fisheries and salt production are predominantly done and important for livelihoods. Sand winning, trade, transport and tourism also take place in the Delta (Codjoe et al. 2020). The delta consists of extensive wetlands, interspersed with areas of mainly red mangroves and savannah forests (Manson et al. 2013).

Decrease in sediment supply to the delta beach system affects its topography and evolution. It exposes the deltaic environment to severe ocean waves attack, which increases the risk of the inhabitants. The Volta delta is dominated by natural shoreline change patterns inherent to large deltas (Anthony et al. 2019). The Volta River is one of the main sources of sediment supply to the Delta, but its activities have been interfered by anthropogenic pressure. The magnitude of sand bypassing the Volta spit (Anthony et al. 2019) has not been sufficient to balance the strong longshore sand transport potential in this drift pulse zone, hence the strong and chronic erosion in the Keta area. The Delta spit as well as the beach fronting it is facing various degrees of erosion as a consequence of diverse scenarios.

Firstly, the sediment discharge from the Volta river has declined over the years (Anthony et al. 2016), being reported at 1 million m<sup>3</sup>/year (Anthony and Blivi 1999), 2.5 million m<sup>3</sup>/year (Allersma and Tilmans 1993) and 71 million m<sup>3</sup>/year (Boateng et al. 2012) before the construction of the Akosombo Dam, but was reported at 7 million m<sup>3</sup>/year in the post-dam construction era (Boateng et al. 2012). Through sediment dating, Nyarko et al. (2016) confirmed that sedimentation rates around the Volta estuary declined rapidly from 1.08 gcm<sup>-2</sup>y<sup>-1</sup> in the pre-dam construction era to 0.50 gcm<sup>-2</sup>y<sup>-1</sup> (50%) post-dam construction (Jayson-Quashigah et al. 2019). These suggest the impact of this



**Fig. 4** Map of the Volta Delta area depicting the 5 m contour boundary of the delta and the nine administrative districts partly or wholly within the delta (Codjoe et al. 2020)

man-made infrastructure not only on the Delta but on the entire coastline. It is further reported that this dam construction affects the coastlines of neighbouring countries involving Togo and Benin because their main source of sand is from sand bypassing the Volta spit trap and sand released by shoreline erosion in the Keta drift pulse zone (Anthony et al. 2019). In addition, the river discharge is different (1000 m<sup>3</sup>/s) in the dry season from (6000 m<sup>3</sup>/s) in the wet season (Anthony et al. 2016). Secondly, the building of the Tema Harbour in 1955 triggered diffraction of sea waves along the eastern coast of Ghana, that resulted in severe erosion (Ly 1980; Tsidzi and Kumapley 2001). Erosion rates that were about 4 m per year in the 1960's increased to about 8 m per year in the 1980's (Ly 1980). Similarly, the construction of a fishing harbour in Tema, west of the Volta Delta is believed to have an impact on erosion rates and livelihoods in the deltaic region. The Tema Harbour and its associated industrial enclave function as a centre of attraction for migrants from the Delta. Thirdly, in recent times, groundwater has been extracted for irrigation of farm crops in Keta District, which seems to intensify the sinking of the delta as reported at other deltaic areas around the world (Kortatsi et al. 2005; Appeaning Addo et al. 2018).

Subsidence is further exacerbated by the oil and gas exploration (Setordzi and Nyavor 2015). Mangroves in the Delta are harvested, decreasing their resilience to fighting erosion and flooding (Anim et al. 2013).

There has been a transition in the Volta Delta from the Holocene to the Anthropocene, however, it is evident the physical features of the delta area are severely altered by human activities and reshaped the nature of human settlement, livelihoods and movements. Particularly, the dam has interfered with the sedimentation process and the repositioning of the river mouth along the Gulf of Guinea and have also reduced the amount of freshwater flowing into the sea. In addition, the population of fish flowing from upstream has decreased considerably. Thus, there has been a migration from the delta area to upstream areas for freshwater fishing. The disturbed ecosystem is adversely affecting livelihoods, although efforts have been made to reduce these impacts, both in terms of infrastructure and policy. Climate change-related phenomena such as rainfall variability, marine and river flooding, drought, sea level rise, storm surges and temperature increase are some of the natural factors changing biophysical conditions in the delta system (Appeaning Addo et al. 2018).



Erosion in the Volta Delta was first reported in 1929, but has been assumed to exist since the 1860's, particularly in Keta (Nairn et al. 1999).

Due to the challenges listed, by 1996, the rate of erosion and flooding had increased (Fig. 5), with more than half of Keta and its surrounding cities submerged (Ile et al. 2014), and left over 10,000 people homeless within Keta. This also caused losses in millions of dollars (Oteng-Ababio et al. 2011; Danquah et al. 2014). Following this, the government of Ghana instituted over US\$83 million Keta sea defence project (KSDP) in 2001 using steel sheets for the protection of about 1.6 km of coastline in the Keta Municipality. From 2001 to 2004, 7 separated groynes were built on the beach of the Keta area to prevent erosion and control flooding of buildings between the Delta and the sea (Boateng 2009). Before KSDP, the communities in and around Keta, led by their traditional leaders and the government had attempted to protect this coast in 1923. These defence structures of the colonial era were however weak local materials that could not withstand the strong waves of the sea (van der Linden et al. 2013). The KSDP was to reclaim the land lost to the sea. In addition, there is currently the building of caves along the coasts of Keta and Ada. The caves were about 190 m long and 750 m apart (Nairn and Dibajnia 2004). In 2011, the government of Ghana began construction of a 30-km marine defence wall in Ada to protect communities from wave action (Anim et al. 2013).

In all, the Delta beaches are highly dynamic with mixed erosion and accretion in response to wave regimes and human

interventions around the Delta and along the coast. The defence structures show two effects: accretion on the upstream side and increased erosion on the downstream side of the coast (Wiafe et al. 2013; Appeaning Addo 2015; Jayson-Quashigah et al. 2019). Sediment volume input is higher on the eastern side of the Delta compared to the west due to inputs from local sources. The construction of the caves has also resulted in significant rates of accretion and the reshaping of the morphology along the coast. The KSDP and the accompanying resettlement plan continue to have some impact on the physical nature of the delta, as well as on human mobility. The construction of the revetment at Atokor in Keta Municipality has also enabled the reconstruction of the previously destroyed road and opened the area to commercial activities. Finally, human settlements, land use and economic activities continue to reshape the land cover and biosphere of the delta area.

To ensure effective and efficient solutions, management options should be broadened. Measures that can reduce the impact of waves while remaining durable for a long time should be tested. As was observed in Keta, in front of the Volta Delta, only the situation of 7 groynes could not absolutely prevent erosion towards Togo though there exist accretion towards Accra. This solution has not been able to stop flooding in the district. In essence, integrated management approaches are encouraged especially solutions that do not produce knock on effects on adjacent beaches. For instance, an integrated approach on this low-lying deltaic coast would be the institution of seawalls in complement with groynes or gabions. In this way, the groynes would protect the seawall



**Fig. 5** Left: Visible beach area, building with sea defense system at Fort Prinsensten, Keta. Right: Massive erosion with no beach and property loss at Prinsensten, Keta in 1985, Ghana

from collapsing, ensuring accretion updrift, and at the same time, the sea would prevent flooding. Individual solutions already deployed, have their advantages and limits, a combination of coordinated solutions at different scales (the scale of the problems, from river coordination to harbours dikes discussion at international, national, regional and local scales) could be the best, with a sequence of mitigation strategies: short term (e.g. sea walls, groynes), medium term (soft solutions such as beach nourishment) and long terms (e.g. natural dune restoration and mangrove afforestation), relocation and improve coastal policies at local, national and international concertation. Thus, an integrated approach is highly encouraged to augment the sediment deficit, and improve resilience. Policy makers should enforce legislation as well to reduce negative human impacts and degradation.

### Complex vulnerability origin and remediation strategies at Saint-Louis, Senegal

The lower stretch of the Senegal River is diverted southwards by a 30 km long sand spit, where the city of Saint-Louis is located. The sandy area of the Langu de Barbarie sandspit separates the terminal from the Atlantic Ocean. The spit was mainly built with sand from the north (Mauritania) and transported by a strong littoral drift (Barusseau 1980). The interaction between fluvial and marine induced sedimentary regimes is of primary importance for the evolution of the spit and natural changes in coastal dynamics revealed the high sensitivity of the mouth and nearby coastal region to any change in the sedimentological and hydrological regime of the Senegal River (Barusseau et al. 1998). In addition, the socio-ecological systems of the delta and along the Senegal River valley have long relied on very subtle adaptations to annual variations in rainfall and river flow/drainage (Dumas et al. 2010). Therefore, the construction of hydraulic infrastructures such as the Manantali and Diama Dams have greatly modified the hydrological conditions in the middle delta and estuary. Since late 1980's, the Senegal River Valley, located in Mali, Senegal and Mauritania, has been gradually transformed into a more artificial location with the construction of embankments, free-flow channels, ditches and drainage gates (Dumas et al. 2010). These hydraulic structures were developed in direct connection with the construction of two larger structures, the Manantali Dam, located upstream in Mali, and the Diama Dam, the first to be completed, in 1986, near the mouth of the river in Saint-Louis (Fig. 6).

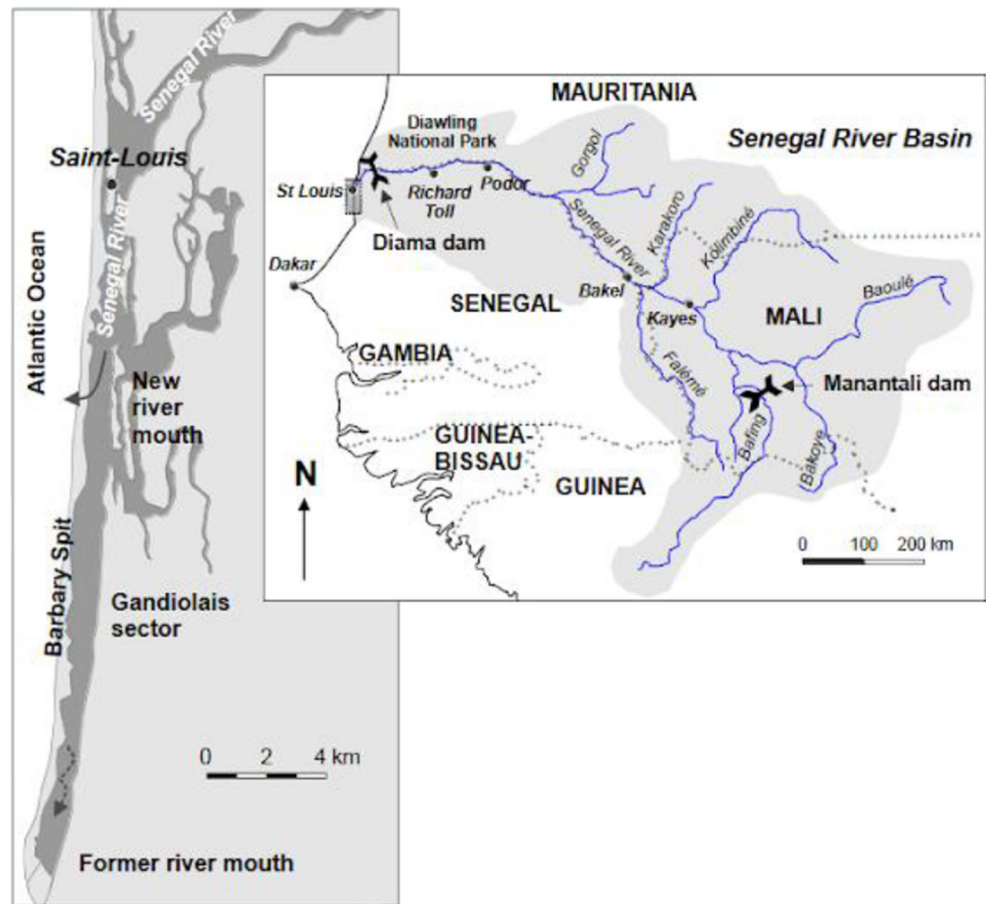
As a tropical savannah river, the Senegal River contributes a terrestrial input, mainly as a suspended load during floods, but this suspended matter does not influence the sedimentary budget of the coast dominated by the waves of the Senegal Delta (Barusseau et al. 1998). However, although sand input played an important role in the construction of the delta by feeding successive Holocene beach barriers (Monteillet

1986), subsequent observations show that the current sediment transport is less dependent on fluvial input. The textural composition of the sediments on both sides of the beach barrier indicates that the input of sea sand, through the coastal drift that moves from north to south, is the main contribution to the construction of the spur. In this respect, the situation after the dam does not change much (Barusseau et al. 1998). On the contrary, the hydrodynamic regime in the outer estuary was significantly modified, as shown by the morphological reworking of the banks. The fluvial influence has been considerably attenuated, so that the main transformations were the result of the dominant action of marine factors.

The Senegalese coast north of the river mouth tends to suffer erosion in the north as well as in the deeper parts of the coast, while accretion is prominent in the south. Therefore, the estuarine-induced forcing of the lower stretch of the Senegal River, downstream of Diama Dam, has greatly disturbed the topography of the mouth and the balance of the coastline. The marine factors have been reinforced, which implies the lengthening of the barrier of the beach of the Langu de Barbarie, the narrowing of the mouth and the accumulation of the mouth bars (Barusseau et al. 1998). Coastal erosion is being strongly felt in Saint-Louis and at least no measures have yet been taken to address the effects of the dams on coastal sediment supply.

The city of Saint-Louis (Fig. 6) is located at the mouth of the Senegal River, in a sandy area with strong hydro-sedimentary dynamics. The central zone is rather exposed to risks of hydrological immersion (flooding of the river). To remedy this, a gap was opened in 2003 in the Langu de Barbarie (~10 km of sandy arrow) and thus improved the water outlet. This gap has continued to grow and migrate southward, exposing many villages to wave erosion and marine submersion, as well as saltwater intrusion, which is problematic for crops and freshwater drinking water resources. Today, the Langu de Barbarie is in the process of recovering and will return to its initial situation in a natural cycle of 15 to 20 years after its opening. But the most urgent problem to be addressed is the north of the rift. This is the erosion/submergence of the very dense Saint-Louis fishing district, built as close as possible to the ocean directly onto the sandy spit. However, this part is being eroded several meters a year (1–3 m according to sources) and entire sections of the district have already been eaten away. The construction/urbanisation of this natural coastline favours an acceleration of the phenomenon limiting the natural resilience capacity of the coast. The problem is that this sandy spur is located in an oceanic environment dominated by strong oblique tides (waves) that lead to one of the most powerful coastal drifts in the world, of the order of 1 m/s, a real river, dragging 800,000 m<sup>3</sup> of sediment per year. Therefore, few "classical" structures (dikes, etc.) can be envisaged. In the very short term, it is planned to protect the exposed neighbourhoods with a protection

**Fig. 6** The Senegal river basin and its new mouth (Dumas et al. 2010)



measure such as the riprap, to improve the effectiveness of the wall currently in place, which has little impact. A parallel scenario is envisaged a longer term planning with relocalisation strategies, together with geomorphological forecasts of Saint-Louis area. This clearly shows the need for a temporality in solutions that should be considered in combination and maybe also in sequence, each one being the best on a specific spatial and temporal scale.

**Conclusions and recommendations on the integration of solutions for improving coastal management**

The coastal area is not only a place of natural marine processes and habitats but shoreline activities inshore and offshore operations and inland activities that output at the coast through drainage systems that flow into the coastal area. An assessment of the systems has shown that an action at one location is likely to have an impact at another location. The development of the ICZM plan takes this as the basis for holistic planning (all components are taken into account). This is seen as a more sustainable approach to coastal management that seeks to link users/processes together, rather than focusing on a single

particular issue. From Senegal across the Gulf of Guinea to the end of Bight of Benin, the system of dividing coastlines into areas that can be managed holistically through:

1) Witnessing the changes - reinforce the monitoring, uniformly at regional West Africa scale of information by gathering to testify the dynamics and quantify what is taking place at the coast, the protections and action needed and suitable, but also follow the efficiency of applied solutions and identify potential environmental or/and sociological locks. Promote the observation network and generalise the centralisation of data and sharing of open data (Find, Access, Interoperate, Reuse). In short, the evolution of the coasts of West Africa is little known and the processes that cause these dynamics are poorly described (i.e. climate change is always perceived as the dominant driver of coastal changes, which is incorrect, human pressure and local infrastructure are often dominant). The creation of networks of scientists and engineers and companies. Strengthen the existing education system (master's degrees, doctorates, thematic workshops on concrete problems and solutions).

2) Identify and involve all stakeholders at the scale of the issues (i.e. sediment cell, rivers basins), who may change over time and space, who are responsible for planning and protecting the coasts, but also users (e.g. communities) and

scientists with multi-level inputs: scientific, operational, governance. Agree on coordinated plans that will achieve the key objectives of stakeholders, using a multi-spatial scale approach adapted to the problems; some problems are local but most are regional, so only regional solutions are appropriate and will provide effective remediation. Social engineering is fundamental (i.e. the best objective solution cannot be accepted by the local population and has to be explained and discussed and/or adapted).

3) Follow sustainable strategies with a multi-temporal solution and anticipate changes, or adaptive solutions using various solutions in combination and synergy with different time frames (e.g. Saint-Louis, a short-term seawall, followed by relocation plans). Manage natural and human systems responsibly. Consider changes in coastal systems and anticipate potential impacts and adapt plans accordingly. A solution adapted to the current pressure or context (current sea level or population density) will fail with changing demographics or climate change. Planning is key.

### Compliance with ethical standards

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