The coastal system of the Volta delta, Ghana
Strategies and opportunities for development

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The coastal system of the Volta delta, Ghana

Opportunities and strategies for development

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Hydraulic Engineering

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23rd January 2018

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Preface

This report is written for the Delft Deltas Infrastructure and Mobility Initiative (DIMI) Volta delta special case. In extension on the workshop in the Volta delta, early October 2017, a literature review is produced to bundle the existing knowledge of the coastal system of the Volta delta and to process this knowledge in practical handles for design.

A lot has already been written about the West-African coastal system and the Volta delta in particular. Scientific literature from various disciplines is available. This report is written from a Hydraulic Engineering perspective with a focus on the coast. It aims to bundle and summarise the existing knowledge to give, amongst others, engineers, architects and policy makers the right handles for future designs and measures.

The report consists of three chapters. Chapter 1 provides a literature review of the Volta delta. In Chapter 2 the current coastal system and recent protection measures will be discussed. And in Chapter 3 design indicators and suggestions for viable solutions are presented.

A nomenclature and list of acronyms are included in the back of the report to provide a description for most of the used concepts and jargon. The inclusion should be helpful in the understanding of the report.

I would like to thank Peter van Veelen for the opportunity and the confidence, to let me write the report.

L.W.M. Roest,
Delft, 23rd January 2018

Abstract

The Volta delta is a very dynamic environment, forming the interface between the Volta river and the Atlantic ocean. The delta is a home for many communities, settled both at the shorelines and more inland. Furthermore the delta provides great natural values and a habitat for many species.

The coastline of the Volta delta suffers from erosion, threatening these communities and natural habitats. Furthermore the delta largely consists of low-lying lands which are prone to flooding. The large scale geology and morphology of the delta are explored and the natural forcing of the coastal system is determined in terms of waves, currents and human impact.

Lastly flood protection and mitigation strategies are explored for the area. It must be noted that in ultimo hard protection measures will not provide a definitive solution. Maintenance is key in any kind of coastal protection strategy. Hard structures are very costly to construct and maintain, although nourishments may not be suitable in every location. More dynamic solutions and retreating from the most hazardous locations would be a better and more sustainable way forward.

Contents

Chapter 1

Description of the Volta Delta

1-1 Introduction

The Volta delta is the coastal plain of the Volta river. It is situated along West-African coast in the eastern section of the Ghanaian coast. The Volta is one of the major rivers of West-Africa with a drainage basin covering large parts of Ghana, Togo and Burkina Faso as well as small portions of Côte d'Ivoire, Mali and Benin, see Figure 1-1.

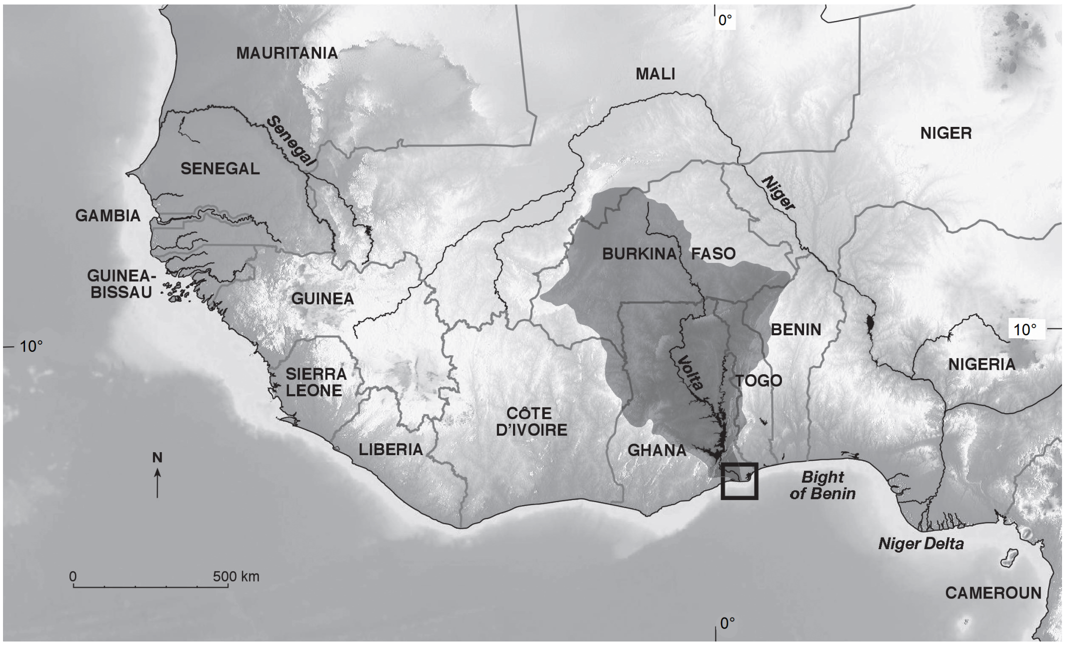

Figure 1-1: Map of West-Africa, showing the Volta basin (dark shade) and the Volta delta (rectangle). From: Anthony et al. (2016).

The deltaïc coast suffers, amongst other problems, from coastal erosion. This coast is characterised by a narrow sandy beach barrier, fringing a low-lying coastal plain, mangrove or lagoon environment. Erosion of the beach barriers threatens the many coastal settlements, as well as natural environments.

This report will focus mainly on the physical processes that play a role in the Volta delta, primarily on the coast. The goal is to provide handles for the design of flood protection and reduction measures, as well as to explore the (im-)possibilities of certain engineering strategies.

The report consists of three distinct chapters. In this Chapter of the report the existing literature will be explored and summarised. Combining the existing knowledge on the Geology, Oceanography, and Hydrology of the delta an overview of the system is created. Furthermore some physical processes and process interactions are described.

In Chapter 2 the largest coastal defence projects are discussed, as well as the natural system. Lastly, in Chapter 3 the boundary conditions are determined and strategies for future development are presented.

1-2 Geology

The Volta river is one of the major rivers of the African continent with a catchment area of $0.4 \cdot 10^6 km^2$ (Ly, 1980). The Volta river drains into the Atlantic ocean through its estuary in the Volta delta. This Volta delta is a seaward protruding lobe shaped delta of $5000 km^2$, on the eastern part of the coast of Ghana (Anthony et al., 2016), see Figure 1-1.

Judging from the large-scale features of the delta, it can be classified along its dominant forcing mechanisms into the Galloway (1975) triangular diagram for deltas, see Figure 1-2. Since the Volta has built a lobe-shaped delta off the coast, it has both features of (river)sediment and wave domination. The sediment domination is expressed by the seaward protrusion of the delta off of the bed-rock, rather than a land-sided incarving. Historically there has been an abundance of riverine sediment input into the system. The wave domination becomes clear from the smooth coastline contour. The tides are of minor importance on shaping the Volta delta, as the width of the estuary remains limited and there is only one main channel. In tide dominated deltas usually multiple channels are present. (Bosboom and Stive, 2015).

Sediment input to the delta by the Volta river has reduced due to blockage of the river by the Akosombo (constructed 1961) and Kpong (constructed 1982) hydropower dams (e.g. Ly, 1980; Anthony et al., 2016). Considering the reduced sediment input from the river to the delta, by reduced discharge and the Akosombo hydropower dam, the Volta delta has now shifted away from sediment domination and more towards a wave dominated delta.

The Volta delta was built by the input of riverine sediments during the Holocene. The surplus of sediments have built the delta lobe off of the original bed-rock shoreline (Ly, 1981), see Figure 1-3. In several parts of the Volta delta the sub-soil has been investigated with bore holes. The organic layers in some of these samples haven been dated using the C-14 method. The cores show a multi-layered soil system, with peat layers dated at 5000-7000 years Before present date (B.P.) (Streif, 1983). This indicates that the current perimeter of the delta is already in this approximate position for an extended amount of time.

Historically sediments from the Volta catchment area have been transported downstream towards the ocean. Estimations are in the order of $10^6 m^3$ per year (Anthony and Blivi, 1999; Ly, 1980). The coarser sand fractions are transported by the littoral drift towards beach ridges to the east of the river mouth. The finer mud and silt fractions, input by the Volta river, have formed a plume on the shoreface east of the river mouth and on the shelf (Ly, 1981;

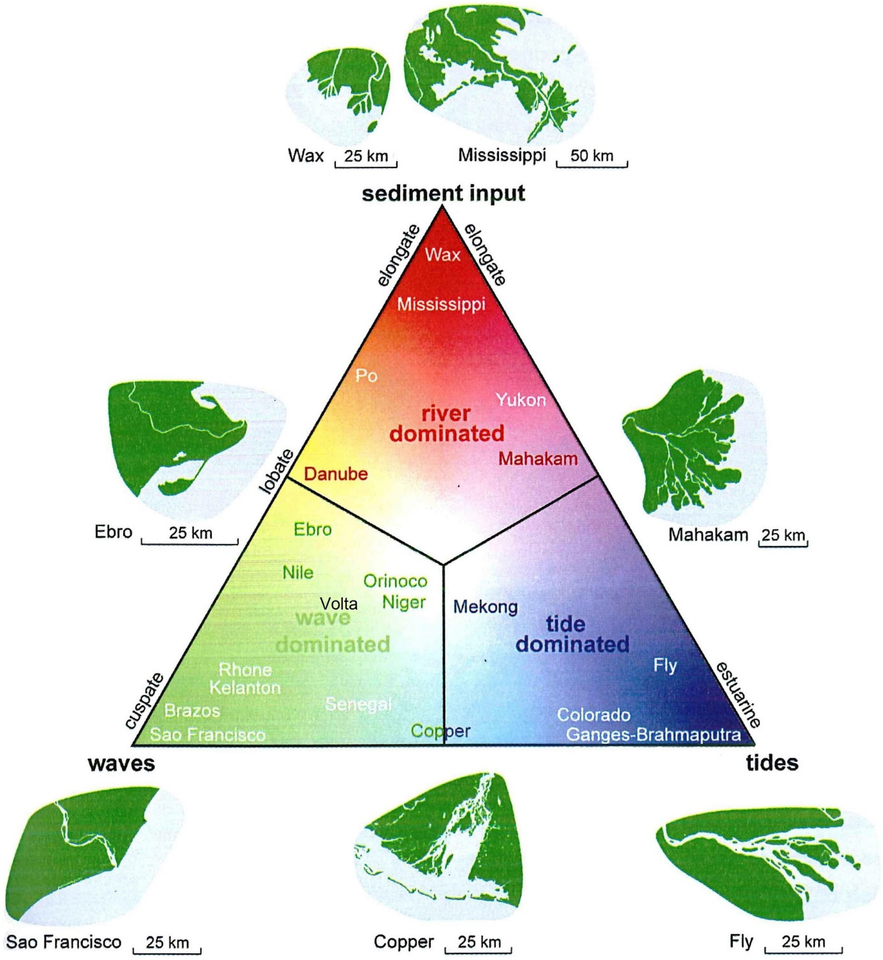

Figure 1-2: Galloway (1975) delta classification diagram, as adapted by Bosboom and Stive (2015), the Volta delta is predominantly wave dominated with historically also sediment domination.

Anthony and Blivi, 1999). The Volta river therefore only supplied sediments for the east part of the delta. However, this influx has diminished due to blockage by the Akosombo (1961) and Kpong (1982) dams. Currently the Volta supplies only small amounts of sediment from the riverbanks downstream of the dams (Ly, 1980). Most sediments currently surfacing at the beach have their origin in up-drift beaches and outcrops, just like the beaches west of the river mouth. Furthermore, no sediments are transported from the deeper shoreface towards the beach (Ly, 1981). Consequently, due to a lack of net input of sediment, the shorelines of Ghana are slowly retreating.

The sediment input from the Volta river has not only built the delta, but also formed the beach barrier system in the bight of Benin, up to 400km east of the river mouth (Anthony and Blivi, 1999). Reduced sediment input by the Volta and human impact (ports, breakwaters) have lead to widespread down-drift erosion. This erosion is most notable east of the deep water ports of Lomé, Cotonou and Lagos. Contrary on the up-drift side of these ports accretion is found.

The barrier system east of the Volta estuary has a multi-layered stratigraphy, for illustration

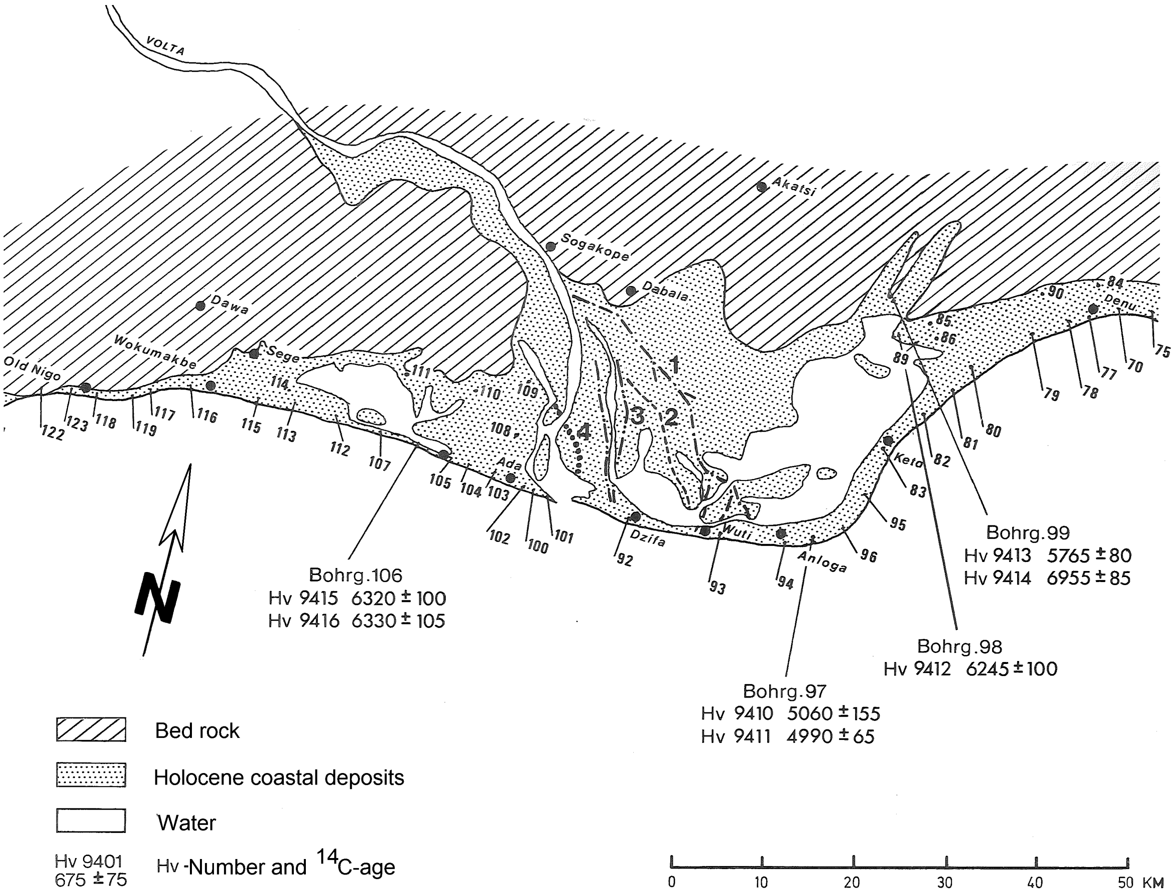

Figure 1-3: Indication of fluvial and coastal deposits in the Volta delta area, being geologically recent (Holocene) as opposed to the bed rock (Pleistocene). Former channels of the Volta are indicated, as well as borehole locations and dating of the subsoils. Adapted from Streif (1983).

see Figure 1-4. The present-time top layer consists of relatively coarse sand with a D_{50} of 0.6mm, which resides on a layer of finer sand and silt. Further down, a coarse sand and gravel layer is found, which subsequently resides on a silty clay layer at depths larger than 20m below Mean Sea Level (MSL) (Anthony and Blivi, 1999). This last layer usually forms the bed of the coastal lagoons. It is assumed that the Volta delta consists of a similar stratigraphy.

In the Volta delta two large and several smaller lagoons are present. These lagoons are shallow, people are observed standing hip-deep in the middle. The bottom of the lagoons consist of a Holocene clay and peat layer, dated 5000-7000 year before present. This layer extends more seaward below the current beach barrier (Anthony and Blivi, 1999). The lagoons will be further discussed in Section 1-4.

Behind narrow and low parts of the beach barrier, over-wash fans are found. These are fan-shaped sandy deposits formed by beach sand which is washed over the barrier by wave over-topping. Especially along the Songor lagoon in the west of the delta area, villages (e.g.. Totope) are built on old over-wash fans. These fans are probably only a few metres thick and prone to settlement of the sub-soil.

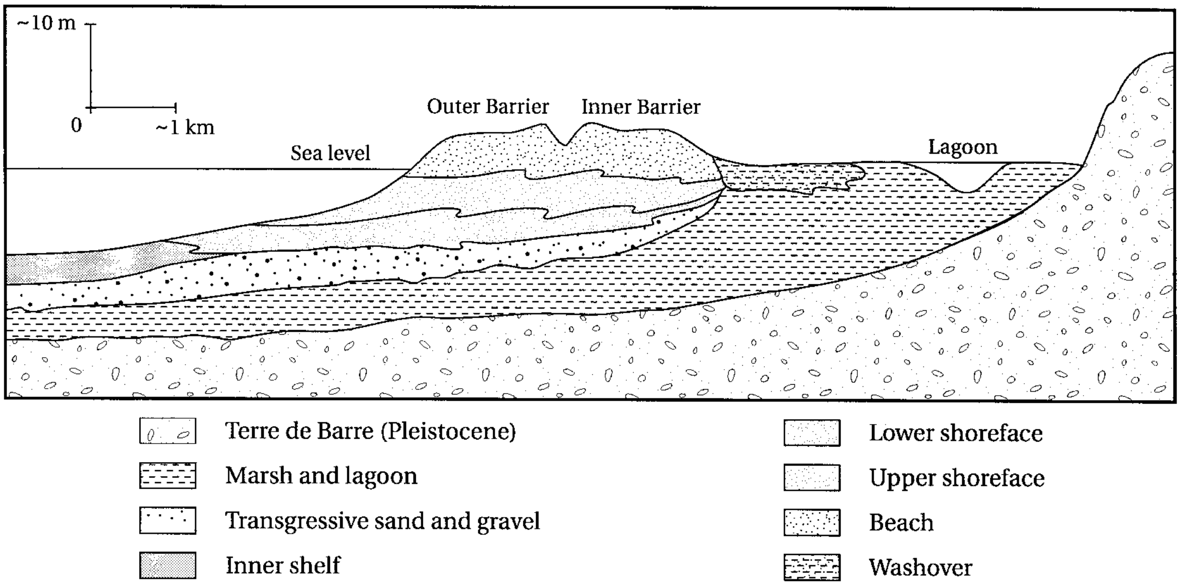

Figure 1-4: Schematic interpretation of barrier and lagoon stratigraphy, based on borehole data, field observations and correlations with deposits in Benin. From: Anthony and Blivi (1999)

From aerial photographs several abandoned channels of the Volta can be identified, between the current main channel and Anloga (Streif, 1983), see also Figure 1-3 This means that the Volta estuary has moved to the west. It is unknown whether these channels still discharge water during extreme discharge events.

1-3 Oceanography

The coast of Ghana is influenced by oceanic gyral circulations. These are the large (ocean basin) scale flows in the oceans, generated by prevailing winds, the Coriolis effect and ocean basin bathymetry. Several large scale ocean currents flow through the gulf of Guinea, the waters off-shore of Ghana. The most dominant one is the Guinea current, which flows to the east at the surface of the water column. Speeds vary throughout the year, with local maxima of 2-3 knots (1.0-1.5m/s) (Wiafe et al., 2013; Houghton, 1976). On average the Guinea current flows at 0.7-0.9 knots (0.3-0.5m/s) to the east, however under strong easterly winds the flow may reverse (Ingham, 1970). At depths larger than 40m there is a counter current, with lower velocities in westerly directions. The depth of the pycnocline is around 40-60m waterdepth (Wiafe et al., 2013; Houghton, 1976; Ingham, 1970). These magnitude of these currents declines towards the coast and cannot transport large amounts of sediment, but can enhance the wave driven transport.

Surface waters are generally warm with temperatures varying from 26°C to 29°C. During strong upwelling events the surface temperatures may drop to 20°C (Ingham, 1970).

In terms of tides, the Ghanaian coast can be described as a micro-tidal coast, with an average tidal range of 1.0m and maximum spring tidal range of 1.8m. The tidal range increases slightly from west (0.6-1.2m) to east (1.0-1.9m) of Ghana. The phase of the tide is approximately the same along the whole coast, so no tidal currents along the coast are induced (Wiafe et al., 2013; Anthony and Blivi, 1999; Gruwez et al., 2014). The tide is however a relevant driving force for the flow in the Volta estuary. The tidal influence is noticeable at least up till Sogakope (30km upstream), where the tidal range is approximately 0.5m and there is still flow reversal (personal observation, 2017). According to Bolle et al. (2015) the tidal range does hardly decay in the estuary up till 5km upstream. At Sogakope the tidal range is reduced to 0.4-0.6m and also a phase-lag of circa 2 hours is registered. This lag is due to the friction in tidal wave propagation in the river.

The morphology of the river mouth is of major influence on the tidal flow in the river. The higher the flow resistance, the larger the phase-lag of the tide and the lower the tidal amplitude in the estuary and river. A large spit closing the estuary will therefore lead to smaller tides in the estuary, while in the current 'open' situation the tidal range and currents are much larger (damped less).

1-4 Estuarine hydrology

Rainfall in West-Africa generally decreases from south to north, with maximum values near the coast and diminishing towards the Sahara desert. In contrast the central and eastern sections of the Ghana coast receive relatively little rainfall. Here first an increase in the amount of rain is found going inland (Acheampong, 1982). The amount of rain in the Volta delta region is estimated at 800mm/year since 1980, it used to be 1000mm per year in the period 1961-1970. Furthermore there is an approximate 5 year cycle in the amount of rainfall, varying between 600 and 900mm/year (Logah et al., 2013; Acheampong, 1982). Precipitation is concentrated in two rainy seasons, the major one around June and the minor in October.

The Volta river used to be a river with a seasonally varying discharge, but since completion of the Akosombo dam in 1964, it is heavily regulated. The river discharge at the Akosombo dam is on average 1150m^3/s, with slight variations following the energy demand (Volta River Authority, 2011; Andreini et al., 2000). The long-term average from 1965 to 1998 is reported to be 950 to 1100m^3/s (Andreini et al., 2000).

Before dam operations started, the river discharge varied considerably over the year. The peak of the discharge was around 6500m^3/s in September and October. Low discharges of less than 1000m^3/s occurred from December to May (Ly, 1980). In the driest months, the discharge even dropped below 100m^3/s. The current discharge at the Akosombo dam is therefore slightly higher than the low-discharge flow from before the dam.

The high peak discharges often caused flooding of the river banks and in the delta area. Since the flow became heavily regulated by the hydro-power dams, floods rarely occur downstream. This has lead to some urbanisation of the river banks and reduction of soil fertility.

In 2010 the Volta lake reached its maximum water level and the spillways were operated for over a month to release the excess water. The discharge was kept around 1200m^3/s through the spillway, making the total discharge circa 2400m^3/s. This led to flooding in the delta area (Volta River Authority, 2011).

Different operation scenarios have been investigated for the Akosombo dam to aid nature by Logah et al. (2017). The conclusion was that this will have severe impact due to flooding of now inhabited areas when the river discharge exceeds 2300^3/s.

Efforts are being made to keep the estuary open to increase the tides and salt water intrusion to keep out fresh water assisted diseases (Volta River Authority, 2011). This manual breaking of the spit in the river mouth has strong morphological effects on the down-drift coast, see also Appendix A-2. Salt water intrusion is now relatively constant due to regulated river discharge. The salt front reaches 10-15km upstream from the river mouth (Andreini et al., 2000). The distance of salt water intrusion is depending on the tides at sea, upstream river discharge and the morphology of the river mouth. It will reach further inland with low river discharge, high tides and an open river mouth.

1-5 Lagoon hydrology

The lagoons of the Volta delta are not directly connected to the ocean or the river. The beach barrier separates the lagoons from the open ocean, while only some abandoned creeks form a potential connection to the estuary.

These lagoons fringing the Volta delta coast have a complex hydrology, which has been significantly altered by the regulated river discharge (R. H. Hughes and J. S. Hughes, 1992). The main inputs of water are rainwater run-off and ground water flows. Occasionally there may be inflow during high river discharge from the Volta via abandoned channels, which used to be more frequent before dam regulation. Additionally there may be wave over-topping over the coastal barrier during storms. Output of water is dominated by evaporation, and may be possible via ground water flow, see also Figure 1-5. Here a closed coastal barrier is assumed. When the coastal barrier breaches an open connection between the ocean and the lagoon is formed. This will introduce tides and (more) saline waters into the area. These tides may also introduce increased flood risk of the low-lying surrounding areas.

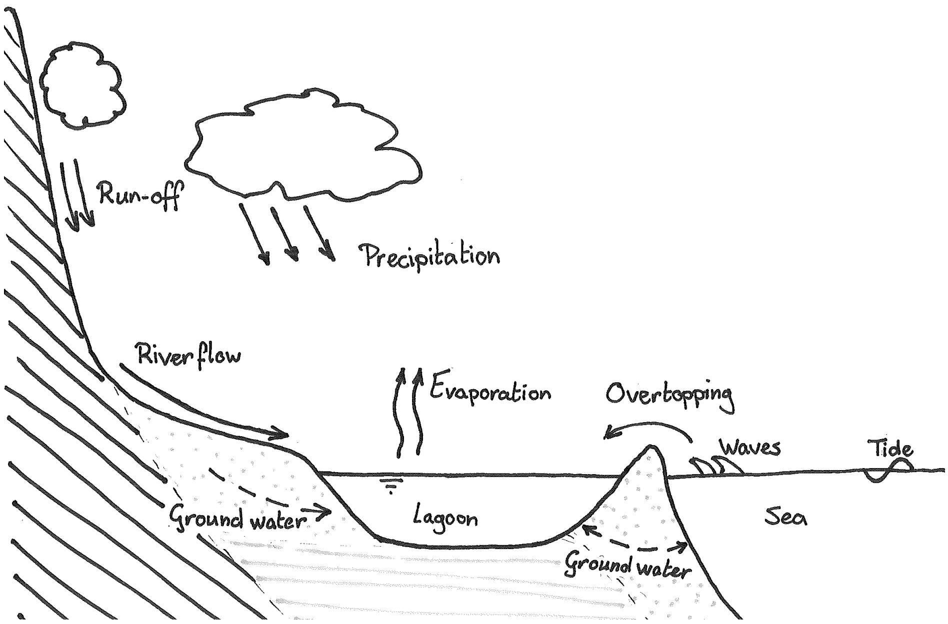

Figure 1-5: Conceptual model of the hydrology of a coastal lagoon, showing the most important fluxes of water.

Besides the lagoons extended areas of marshes and mangroves are found in the delta. These areas dry and flood twice daily with the tides.

1-6 Beach morphology

This section describes the shape of the coastline and beaches, and the important forcing mechanisms. An assessment of coastal erosion and accretion is present in Chapter 2.

The beaches fringing the Volta delta are shaped by the persisting swell waves arriving at the coast. Wave driven sediment transport can be considered the single most important forcing of the Ghanaian coast. The long waves (swell) approaching the Ghanaian coast, in combination with relatively coarse sand cause a steep beach profile (Anthony, 2015). The upper beach face has a slope of approximately 1:3, the lower 1:10 to 1:15. In contrast, beaches in the Netherlands have a slope around 1:150 in the intertidal zone.

The resulting beaches at the Volta delta coast are very steep and narrow. Such narrow and steep beaches are unfavourable for wind driven sediment transport. Together with the moderate wind climate and the coarse sediments, this explains why there are no dunes found along the Volta delta coast. Consequently the height of the beach barrier is relatively low, since hydrodynamic accretion of sediments is limited to the wave run-up level (Roest, 2017).

The actual coastal profile varies considerably along the perimeter of the delta. The resulting cross-sectional shape of the beach depends predominantly on sediment properties (size, shape and weight) and incoming wave energy (height, length, angle).

A different orientation with respect to approaching waves changes the incoming wave energy. Also spatial variation in sediment size (distribution) has to be considered. Further the off-shore bathymetry plays a role, see Figure 1-6. At shallow water[1] the wave celerity is dependent on the local water depth. Due to the local bathymetry, waves will refract and the wave energy is no longer equally distributed over the shore. In contrast on deep water the wave propagation speed is dependent on the wave period only.

Unfortunately, no detailed measurements of the coastal profile are available to make comparisons between sites.

[1]Shallow water: water depth $< 1/20$ wave length, deep water: water depth $> 1/2$ wave length

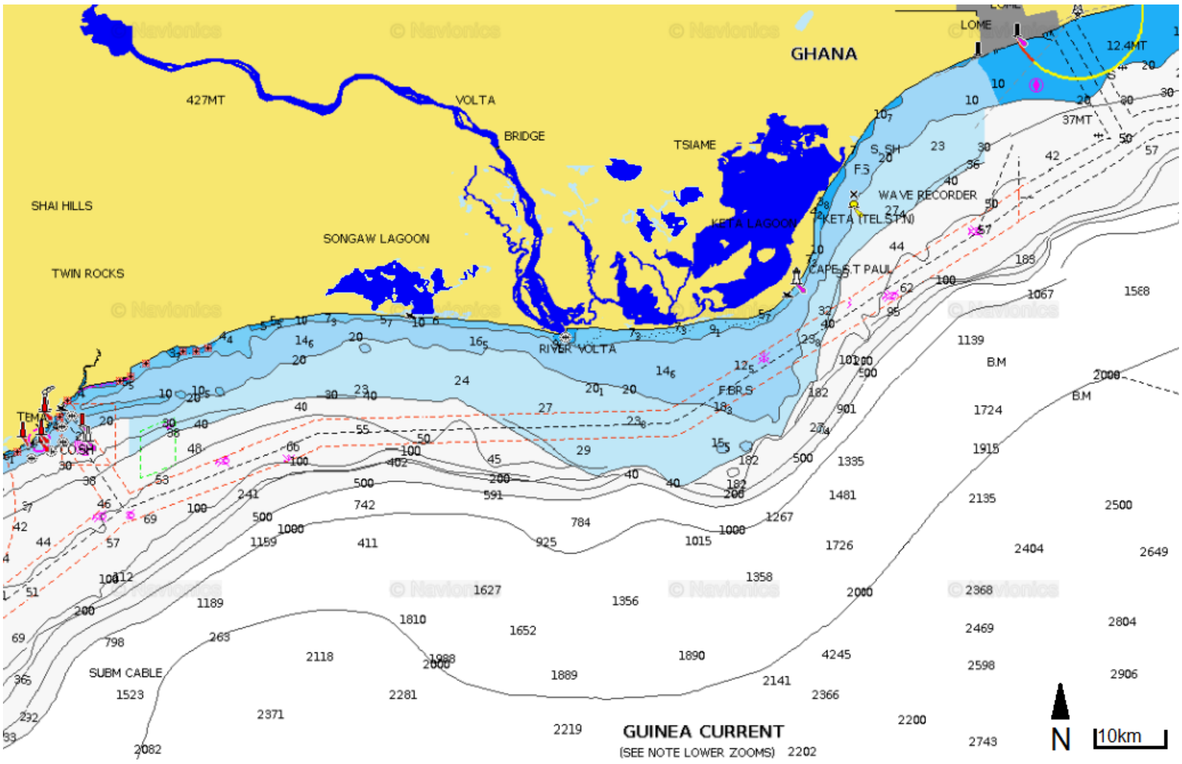

Figure 1-6: Nautical map of the continental shelf of the Volta delta, from Tema (left) to Lomé (right) showing the bathymetry, depths in metres below Lowest Astronomical Tide (LAT). The river has formed an offshore bulge of sediment (light blue). Adapted from Navionics Inc. (2017).

Chapter 2

The coastal system and its interventions

In this chapter the current situation of the coastal system of the Volta delta is described. First the natural system and its behaviour will be described, and further some sites with existing coastal protection works will be examined. In Figure 2-1 an overview is presented of the the parts of the coast where protection measures have been taken.

2-1 The coastal system

2-1-1 Beach-barrier system

The coast of the Volta delta consist of sandy beach barrier, fringing lagoons, mangroves, marshes or low lands. The width and height of the beach barrier varies considerably along the perimeter of the delta. The parts fringing the lagoons are only 100m wide. At other locations (e.g. Anloga, Ada Foah) the strip of land is 1 to 2km wide between the ocean and the lagoon or marsh. In Figure 2-1 coastal barrier areas are indicated in red.

The areas behind the beach barrier consist of shallow lagoons, mangroves or low lying land. The land use consists of natural vegetation, agriculture, or villages, see Figure 2-2. Lagoons are used for fishing and salt mining. Large parts of the hinterland are elevated only up to 2m above MSL and are therefore subject to risk of flooding.

2-1-2 Sediment transport processes

The sandy beach barrier system of which the Volta delta is a part of an extended system of barriers and coastal lagoons in the Bight of Benin, which continues for over 400km. The system has its western boundary just east of Old Ningo (Ghana) and continues all the way past Lagos (Nigeria), where it merges with the mud-dominated Niger delta (Anthony and Blivi, 1999). This coast is believed to have one of the highest rates of Longshore Sediment Transport (LST) in the world (Anthony and Blivi, 1999). Estimates of the rate of LST vary from $0.5 \cdot 10^6 m^3$ to $1.5 \cdot 10^6 m^3$ per year (e.g. Anthony and Blivi, 1999; Allersma and Tilmans,

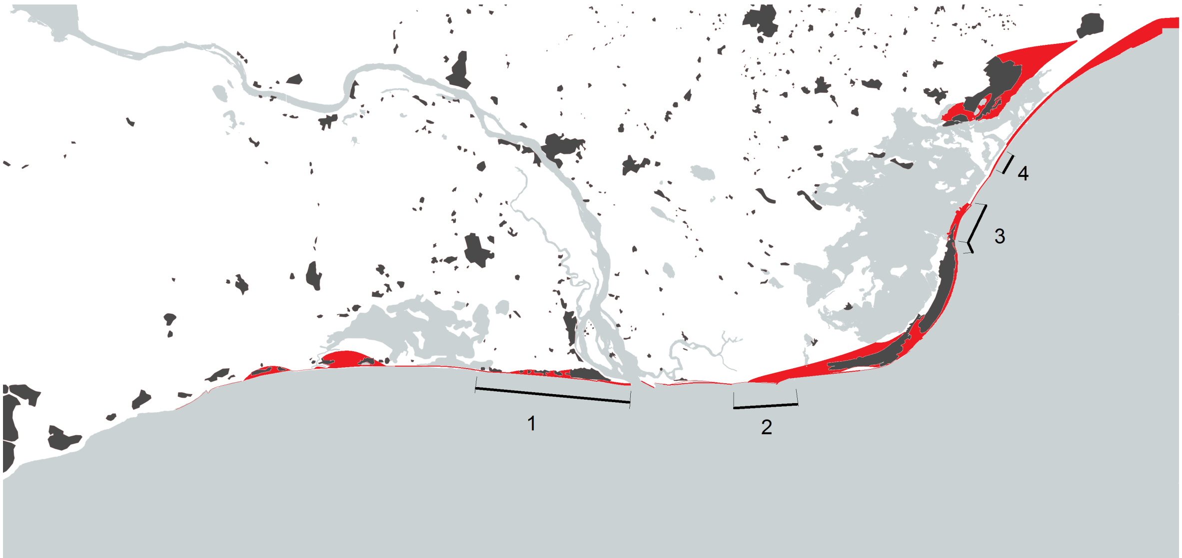

Figure 2-1: Map of the Volta delta showing an indication of coastal beach barriers in red. The width of the barrier type area varies considerably along the delta perimeter. Also indicated are current coastal protection works. 1: Ada sea defence (groynes), 2: Atorkor-Dzita-Anyanui sea defence (revetment and groynes), 3: Keta sea defence (revetment, land reclamation, groynes) and 4: Groynes between Kedzi and Adina.

1993). This means that on average this amount of sediment passes a virtual line perpendicular to the coast at an annual basis.

As the angle of wave incidence to the coast is small, the coastline tends to smoothen and no strong curvature can be maintained. Anomalies formed during extreme events are smoothed out or bypassed, making the coastline almost straight again on km scale. Contrastingly a high angle of wave incidence would cause instability of the coastline, resulting in the formation of shoreline undulations or spits (Ashton and Murray, 2006; Anthony, 2015).

Following the coastline along the delta from west to east, the orientation changes considerably east of Anloga from W-E to more SW-NE. This would cause an increase in wave driven transport, however due to wave refraction over shallow areas the wave energy reduces accordingly (see also Figure 1-6). It is only in the bend near Keta, that some instabilities are observed in the coastline.

The high transport rates makes that any perturbation causing a transport gradient to be smoothed quite fast. This strong reaction also holds for anthropogenic disturbances, such as groynes. As these structures cannot be displaced by wave action, up-drift there will be strong accretion and down-drift strong erosion. Depending on how much of the LST is blocked, these effects can be noticed for kilometres from the groyne. Effects of sea defence projects will be discussed in following sections.

Large parts of the delta shoreline show retreat, leading to loss of land and villages (Ly, 1980; Anthony and Blivi, 1999; Addo, 2015). Therefore in recent years several projects for coastal protection have been executed. The two most notable ones are the Keta and Ada sea defences. On the map in Figure 2-1 it is indicated which parts of the coast are currently protected.

The lower parts of the beach barrier system are subject to wave overwash (or overtopping)

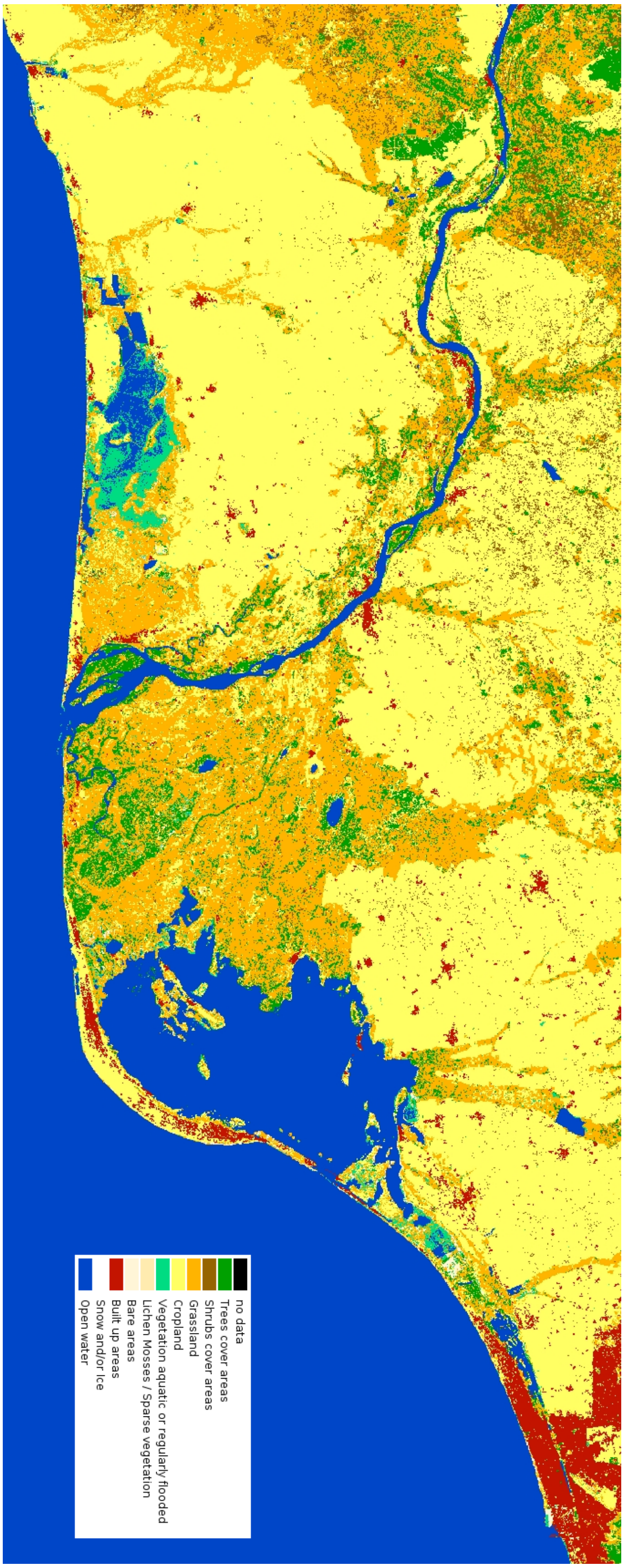

Figure 2-2: Indication of land cover of the Volta delta, areas indicated as grassland may also be marshes. An interactive map-application is available at http://2016africalandcover20m.esrin.esa.int/viewer.php. Derived from: *CCI Land Cover – S2 prototype Land Cover 20m map of Africa 2016* (2017)

during severe conditions. This means that waves are flowing over the barrier. This process transports sediments to the back of the barrier, resulting in overwash fans. When this process continues long enough the barrier breaches and an open connection between the lagoon and the sea is formed. In the long run, even when no breaches are formed, the barrier will slowly migrate landward.

The last sediment transport process to be discussed is sand mining. Sand mining both legal and illegal is taking place throughout Ghana (Angnuureng et al., 2013). Sand mining from the beach is a large sink of sediment from the coastal system and causes retreat of the coastline (Angnuureng et al., 2013). It should therefore be stopped immediately.

2-1-3 Mangroves

Until present day extended areas of the delta are covered with mangroves. These low-lying areas have tidal creeks diverting from the estuary and are thus under the influence of the tides. Mangrove areas generally have an elevation between MSL and Mean High Water (MHW), and are therefore flooded daily.

Due to the sheltering effect of their roots, mangroves can accrete fine sediments. Furthermore peat formation by the mangroves self also increases the bed-level. Under favourable conditions, mangroves are therefore expected to be able to keep up with Sea Level Rise (SLR) (McKee et al., 2007).

It is important to note that mangroves cannot survive in high wave energy conditions, therefore they are not found on the sea-facing beaches of the Volta delta. Instead mangroves are found in the sheltered wet-lands of the delta. This as opposed to the low energy, mildly sloping and muddy coasts of South-East Asia, where extensive mangroves are found directly at the coast. Mangroves are thus unsuitable for coastal protection in the Volta delta, yet vital for the deltaïc ecosystem.

2-2 Keta sea defence project

The first of large scale sea defence projects in the Volta delta area was the Keta sea defence project (mapped 3 in Figure 2-1, see also Figure 2-3). This project, executed between 2001 and 2003 by Great lakes Dredge and Dock Corporation, aims to protect the coastal town of Keta and the beach barrier of Keta lagoon. Furthermore land was reclaimed by dredging for accommodation of the growing population and compensation of lost land (Nairn et al., 1998; Anthony et al., 2016).

Before construction of the sea defence project, Keta had suffered from severe coastal erosion at least since the 1920's and possibly longer (Anthony et al., 2016). Many studies and designs were made between 1960 and 1995, yet much of the town was lost to the sea, before action was finally undertaken. Breaching of the barrier, separating Keta lagoon from the sea, lead to tidal influences in the lagoon and loss of the road connection between Keta and Kedzi (Nairn et al., 1998).

The Keta sea defence consists of multiple structures, each with their own functions. First a rubble mound dam with a road was constructed to reconnect Keta with the main land. In this dam an outlet sluice was constructed to discharge excess water from the lagoon. Subsequently

Figure 2-3: The Keta sea defence project, looking NE. In the foreground the revetment in front of Fort Prinzenten can be seen, while in the background the heads of the groynes are visible.

the beach barrier was reconstructed to restore the longshore drift. Land was reclaimed in a large part of the area between the dam and the barrier. Groynes have been constructed to stabilise the coastline and to preserve the reclaimed land. In front of Fort Prinzensten a rubble mound revetment was constructed to prevent further erosion. Here a revetment was needed because of the proximity of the buildings to the water line (Anthony and Blivi, 1999; Anthony et al., 2016).

While the Keta sea defence is locally very successful in protecting Keta, down-drift coastal erosion is exacerbated due to the partial blocking of the longshore drift. The effects are most severe around Kedzi, but measured and reported as far as the Togo border (Addo, 2015; Anthony et al., 2016). Recently (2016) additional small groynes east of Kedzi have been constructed, as local erosion rates exacerbated. Their long-term effectiveness is however disputable.

Especially in the corner, near Fort Prinzensten, the coastline is unstable and very dynamic. Annual variabilities of over 50m are observed from satellite and aerial imagery.

For the evolution of the Keta coast, see Appendix A-1

2-3 Ada sea defence project

The second largest sea defence project is situated at the west side of the Volta Estuary: the Ada sea defence project (mapped 1 in Figure 2-1, see also Figure 2-4 and Figure 2-5). Ada suffered from coastal erosion, leading to the destruction of a part of the town. Eventually a defence project was agreed upon in 2010 (Bolle et al., 2015; Bollen et al., 2011).

The Ada sea defence is built in two stages between 2012 and 2016 by Dredging International (DEME Group). In total it protects 16km of coast west of the river mouth. The first stage

Figure 2-4: The Ada sea defence project, at Ada Foah, looking East. On the left the nourished beach barrier and to the right a groyne. The step in the coastline is an effect of the groyne partially blocking the sand.

was built in 2012-2013, covering the first 5.5km from the river mouth. The second stage followed from 2014, covering the remaining 9.5km (Bolle et al., 2015; Bollen et al., 2011).

The project consists of groyne fields in combination with beach nourishments. The groynes are spaced at ca. 800m, with a length of ca. 180m. Their function is to partially block the LST and as such reduce the coastal erosion. The nourishment was made into a barrier to protect against wave overwash (Bolle et al., 2015; Bollen et al., 2011).

One of the difficulties in the project was the presence of nesting sea turtles, which should not be disturbed. Furthermore the nourished beach must stay suitable for them (Bollen et al., 2011).

Long term effectiveness is still unclear, since the project is too recent, but as in Keta, the down-drift erosion has become worse. Erosion of the western spit in the Volta river mouth can be largely addressed to the blocking effect of the Ada sea defence (Gruwez et al., 2014; Bolle et al., 2015), see also Figure 2-5. At least growing back of the western spit will be hampered. It is very plausible that the recent (February 2016) flooding disaster in Fuvume can be related to this project.

For an overview of morphological changes near the river mouth see Appendix Figure A-2.

2-4 Atorkor-Dzita-Anyanui sea defence project

East of the river mouth, near the town of Dzita, a 2.7km section of coast is defended by a revetment, built between 2011 and 2014 (mapped 2 in Figure 2-1). Down-drift a 2km groyne field with short groynes is built to ease the transition towards the natural system.

As the sea destroyed the coastal road connection, a defence plan was initiated to reconstruct the road and prevent further erosion. Unfortunately no literature is available on the effective-

Figure 2-5: The Ada sea defence project, at Kewunor, looking south. Visible is the last groyne west of the Volta river mouth (to the left) and the beach barrier to the right. The spit used to extend across the river mouth, but has largely been eroded.

ness of the project. Although from satellite imagery it can be derived that down-drift (east) of the groyne field erosion and shoreline retreat still continues.

2-5 Accretive and erosive areas

Most of the Volta delta shores are subject to structural erosion (Ly, 1980; Boateng, 2012; Addo, 2015). Yet large yearly variations are found. Subsequent assessed intervals by Addo (2015) often show alternating accretion and erosion. Thus annual variability and accuracy of the assessment method (satellite images) are of the same order as the long-term coast line trend. A careful analysis of coastline position based on satellite imagery of the past 33 years would provide the opportunity to distinguish between long-term trends, episodical events and (inter)annual variability. This is now possible using Google Earth Engine

Furthermore the recent construction of hard sea defences have changed the sediment transport rate, leading to different sedimentation/erosion patterns than historically. In general areas down-drift of groynes or rocky outcrops will erode more than average, while areas up-drift of obstructions will accrete or erode less. This all depends on gradients is sediment transport.

Chapter 3

Design considerations

The beach barriers facing the large lagoons should remain uninterrupted, to protect the low-lying hinterland from flooding. Should the water-level in the lagoons ever become too high, controlled breaching (and restoring!) is an option.

As the barrier breaches, it may disappear entirely and the tides and waves then run into the lagoons.

3-1 Design indicators

In this section some parameters are presented which are governing for the design of coastal protection measures.

3-1-1 Wave climate

The wave climate consists of swell waves from south to south-west directions. On average the significant wave height is 1.0m, while annual maxima are around 2.5-3.0m. Waves lower than 0.5m virtually never occur. Superimposed on that, there is also an occasional contribution from local wind waves. However, these are generally low and carry less energy. No persistent storms occur along the Ghanaian coast (Bolle et al., 2015).

The off-shore wave climate is very constant along the Ghanaian coast. Wave modelling by Giardino et al. (2017) shows large variations in the nearshore wave climate. Due to the submerged shallow parts of the Volta delta (see Figure 1-6), the coast between Anloga and Kedzi receives different waves. The waves here are significantly lower and come from other directions, see Figure 3-1 (Giardino et al., 2017).

The waves around Keta cannot approach the coast directly and are being refracted over the shallow parts of the Volta delta. In this process energy is lost, leading to lower waves. The locally milder wave climate also explains Keta's function as port until the construction of the deep water port at Tema (1962).

Some variability is present in the wave climate over the year. In line with the southern hemisphere seasons, the highest waves occur from July to August, while the lowest waves occur around January and February.

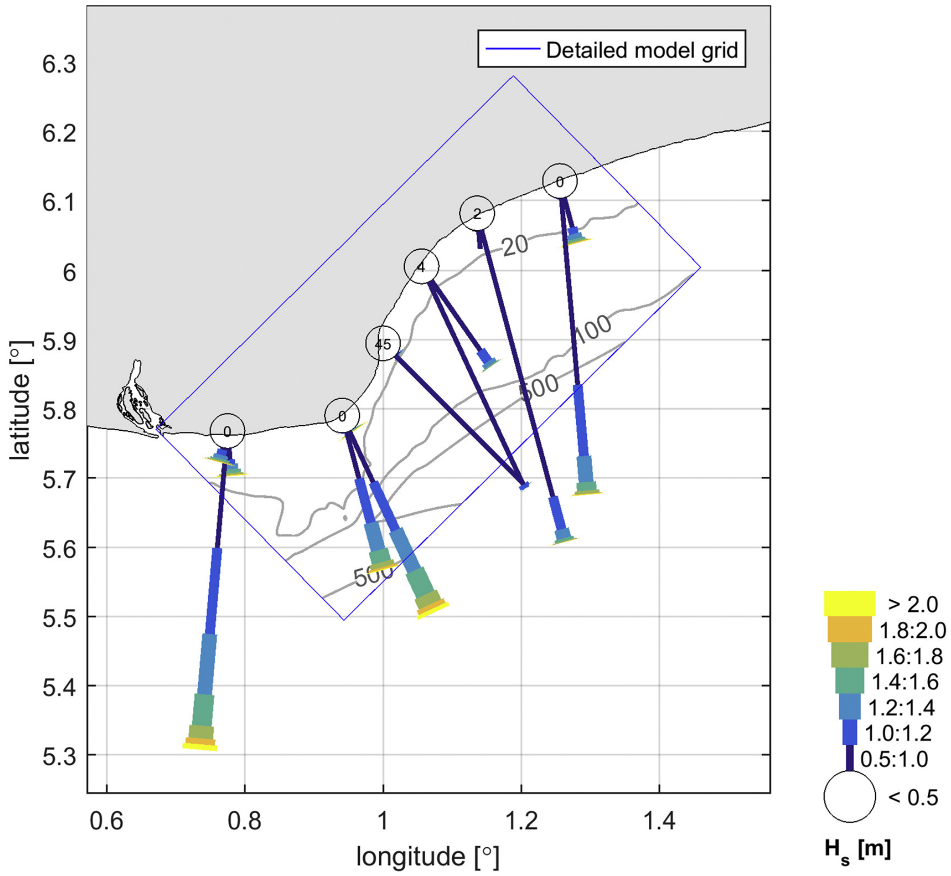

Figure 3-1: Nearshore wave climate in the surroundings of Keta. Wave roses indicate the directional percentage of occurence of a wave height. Near Keta the waves are lower. From: Giardino et al. (2017)

3-1-2 Cross-shore

The morphologically active part of the beach is that part of the beach that shows significant changes in time. Both upper and lower boundaries can be determined. The lower boundary, the largest depth at which the bed-level still changes is mainly dependent on the largest observed wave height (Hallermeier, 2011). Using the (Hallermeier, 2011) formula for the depth of closure, presented in Eq. (3-1), this boundary can be determined.

$$d_{DOC} = 2.28 H_{s,e} - 68.5 \frac{H_{s,e}^2}{g T_e^2}, \tag{3-1}$$

Here H_s is the significant wave height, exceeded for 12h in the desired period and T is respective wave period. Using the nearshore wave data from Giardino et al. (2017) the depth of closure can be determined. On annual time scales the lower boundary is at -4.3m LAT (H_s=2.0m, T=11s). For a 10 year timescale, it is at -7.4m LAT (H_s=3.4m, T=16s).

The upper boundary for wave driven sediment transport can be determined by summation of the tidal water level, the wave amplitude and a factor for wave run-up on the beach. A first order estimate results in 2.8m LAT, for 2m waves during spring tide. Yet run-up levels are hard to determine and very much dependent on the beach profile. A ‘safe’ height for the beach barrier with minimal overtopping would certainly be higher.

3-1-3 Beach profile morphology

Beaches fringing the Volta delta are generally steep, due to a combination of the wave climate and the coarse sand. On the beach a ridge is formed at some level above MHW, moreover this ridge is higher than the hinterland in large parts of the delta. Therefore the beach ridge essentially is a protection against flooding from the sea.

Lagoons are separated from the ocean by a beach barrier, keeping the waves and tides out of the lagoon. Only the highest waves will overtop the barrier, thereby creating overwash fans. The overwash is also a mechanism by which the barrier moves landward, which can be considered coastline retreat but without loosing sediment.

3-1-4 Spatial scales

Here the different spatial scales will be discusses which govern the different coastal processes and therefore the viable solutions. In general length scales are longer along the coast, than perpendicular to it. The same holds for variations or gradients, which are more smooth parallel than perpendicular to the coast. Alongshore significant spatial scales are in the order of 1-10km, perpendicular this is only 10-100m. Vertically scales are even smaller, as changes in the order of 1m are already significant.

3-2 Viable solutions

In this section several coastal ‘protection’ strategies are presented. These strategies cannot be applied just anywhere, yet their most promising locations are indicated on the map in Figure 3-3. The strategies presented hereafter all have one thing in common: maintenance. No single strategy provides an eternal solution, so (regular) maintenance is key.

The following strategies will be discussed: do nothing, managed retreat, nourishments, mega nourishments, hard structures. All of which can be combined in one way or another.

3-2-1 Do nothing

The first scenario one has to consider is what will happen when ‘nothing’ is done, also the reference scenario. When no additional measures are taken the coastal erosion persists, yet it requires no effort. Just letting the coast erode could be considered in locations where no settlements are present, or only far from the coast. No buildings or capital investments should be made in these areas.

Obviously this approach is less suitable for settlement areas currently subject to immediate erosion. The advantage is that no additional disturbances are introduced in the coastal system, so no negative consequences are expected to propagate.

3-2-2 Relocation/Evacuation

Some areas are or will become so dynamic or erosive that they should be evacuated immediately, or in the near future. Existing communities should be relocated and compensated for losses. An example is the area around the river mouth, especially on the east side near Fuvume. The interaction between the sea and the river causes a very high morphological activity, rendering the place unsuitable to live. Areas subject to frequent inundation should also be considered for relocation. The urgency depends on the frequency of flooding and the inundation depth.

3-2-3 Managed retreat

Locations not economically feasible to protect could be designated for managed retreat. A stop for all building activities (capital investments) within a certain reach (e.g. 250m or even more) from the coastline should be announced and the no-building zone should regularly move landward with the coastline. Existing buildings can be maintained until the erosion progresses too far and should be relocated in time. This way the coastal settlements might migrate landward with the coastline. Apart from frequent monitoring of the situation and relocation from the 'retreat area' it requires little investments.

3-2-4 Nourishments

One way to mitigate erosion is placing nourishments, additional sand from another location is then placed on the beach or shoreface. Due to the high transport rates small-scale nourishments are hardly an option. An exception may be the repair of immediate local damage, however that is no long-term strategy.

Mega-nourishments (Sand Engine like) have a longer expected life-time in the order of 5-50 years. As mega nourishment are a recent development in coastal protection, no experience exists in swell wave environments. Additional morphodynamic modelling is therefore required before implementation.

The disadvantage of sand nourishments is that they become expensive when placed on deep (>10m) water, and sea-going dredging equipment is mandatory. Nourishments are mainly attractive in locations where settlements are already close to the shoreline and the shoreface is not too steep. Sediment losses should be minimised in order to maximise the expected life-time.

Nourishments come in different forms, depending on the location where the sand is placed, see Figure 3-2. Beach nourishments are placed on the dry and intertidal beach or on the beach barrier (or dunes). Shore face nourishments are placed below water, usually around 3-5m below MSL. These nourishments change wave breaking and, when well designed, are slowly transported onshore. Lastly, mega-nourishments are placed concentrated in one location and are spread along the shore by waves and currents.

3-2-5 Hard solutions

In directly threatened locations that cannot/shouldn't be evacuated, hard protection measures (e.g. groynes, revetments, dikes) may be viable solutions. When well designed, they will last

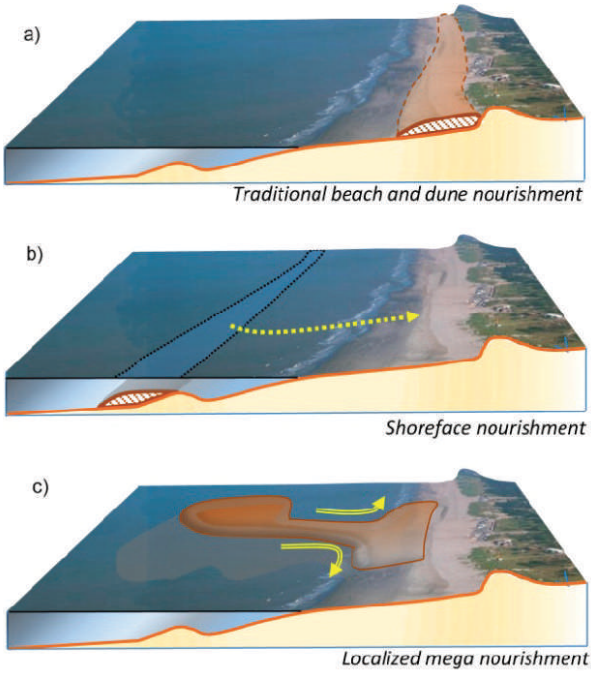

Figure 3-2: Illustration of the placement of different types of nourishments in the coastal profile. Panel a: beach nourishment, panel b: shore-face nourishment and panel c: mega-nourishment. From Stive et al. (2013).

long and are very effective locally. However they have unwanted side-effects, both nearby and up to kilometres further alongshore. Additionally these structure require a large capital investment and are not maintenance free.

The side effects usually are down-drift erosion over distances several times the length of the protection itself and undermining of the toe of the structure due to continuing erosion of the foreshore. Furthermore costs increase sharply with increasing water depth.

Combinations with nourishments are possible. For instance groyne-fields with a beach nourishment between the groynes, as performed in the Ada sea defence project.

3-2-6 Proposal

A schematic proposal for the coastal strategy is shown in Figure 3-3. This proposal is certainly not meant to be a definitive design, but merely a sketch for the potential combination of measures.

Given the current state of development of the area, large scale investments in coastal protection measures are not worth it from a cost-benefit perspective, as also mentioned by Boateng (2012). However there is always a choice not to follow the outcome of a cost-benefit analysis. As a consequence financial costs will be high.

Large scale urbanisation of the delta area should be prevented as it will only increase vulnerability as potential damage increases. Existing settlements can be largely maintained, however the most vulnerable locations should be evacuated and settlements relocated. In the remaining areas construction should be limited to relatively higher areas and a certain distance from the coast should remain clear to adapt for future coastal erosion.

Another important aspect is the integrity of the lagonal barriers. These may move freely, as long as they remain closed. Opening or breaching of these barriers will lead to increased salt intrusion in the lagoons and flood risks of the low hinterland.

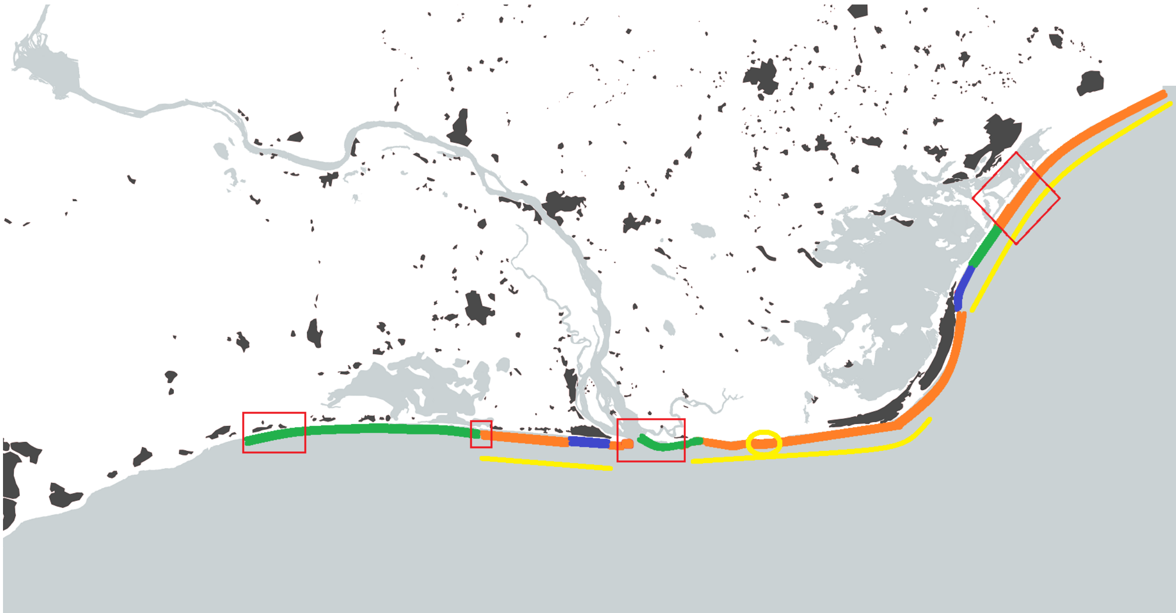

Figure 3-3: Map of the Volta delta coast, displaying the most viable solutions: no measures (green), managed retreat (orange) and hold the line (blue). Viable locations for nourishments are indicated in yellow. A mega nourishment is proposed at the yellow circle. Red boxes are drawn around settlements that should be evacuated in short term as they are too close to the coastline.

A second scenario should be considered where the Volta river is made suitable for inland shipping. The river mouth then needs to be stabilised, which usually involves large breakwaters. The effect on the coast would be enormous. To the east erosion rates become much higher, which could not be easily mitigated. To the west at Ada large accretion is to be expected. This would either lead to large dredging tasks, or mandatory relocation and loss of land. This plan would however involve enormous investments in infrastructure in the river mouth and upstream at Kpong and Akosombo.

A further aspect could be the regulation of water levels and quality in the lagoons for irrigation and intensified fish farming. This would require the construction of channels for the intake of fresh river water upstream and discharge sluices at the coast. Changes in salinity of the lagoons may however have far-reaching consequences for existing ecology.

An aspect that has not been treated yet is the protected status of large part of the delta area. Large areas are appointed as Ramsar-sites, protected by the Ramsar-convention. This convention has as mission: "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world" (The Ramsar Convention Secretariat, 2014). Therefore these areas should be treated with care, which may be in conflict with other interests.

Appendix A

Coastline development

In the next two figures the coastal development in the approximately last 30 years is depicted. Two sites are chosen: Keta and the Volta river mouth. In these locations large dynamics are present and recently sea defences were implemented.

In Keta (see Figure A-1) before the sea defence, the coast was heavily eroding as can be seen in the panels from before 2001. Between 2000 and 2003 the project was built. Nowadays locally the coast is well protected, but remains very dynamic with inter-annual coastline dynamics over 50m. Down-drift erosion has increased.

In the Volta river mouth (see Figure A-2), the western spit has broken down twice (1989 & 2010). The sediments of the spit are moved towards the down-drift coast where accretion of locally more than 100m is observed in a three year time span. These effects are temporary as the erosion continues. Also it is questionable whether the western spit will grow back, due to blockage by the Ada groynes.

Figure A-1: Coastline changes around Keta from 1986 to 2017, imagery obtained from Google Earth (2017).

Figure A-2: Coastline changes around the Volta river mouth and Ada from 1984 to 2017, imagery obtained from Google Earth (2017).

Appendix B

Villages in the Volta delta

The map in Figure B-1 shows the approximate locations of the villages mentioned in the report.

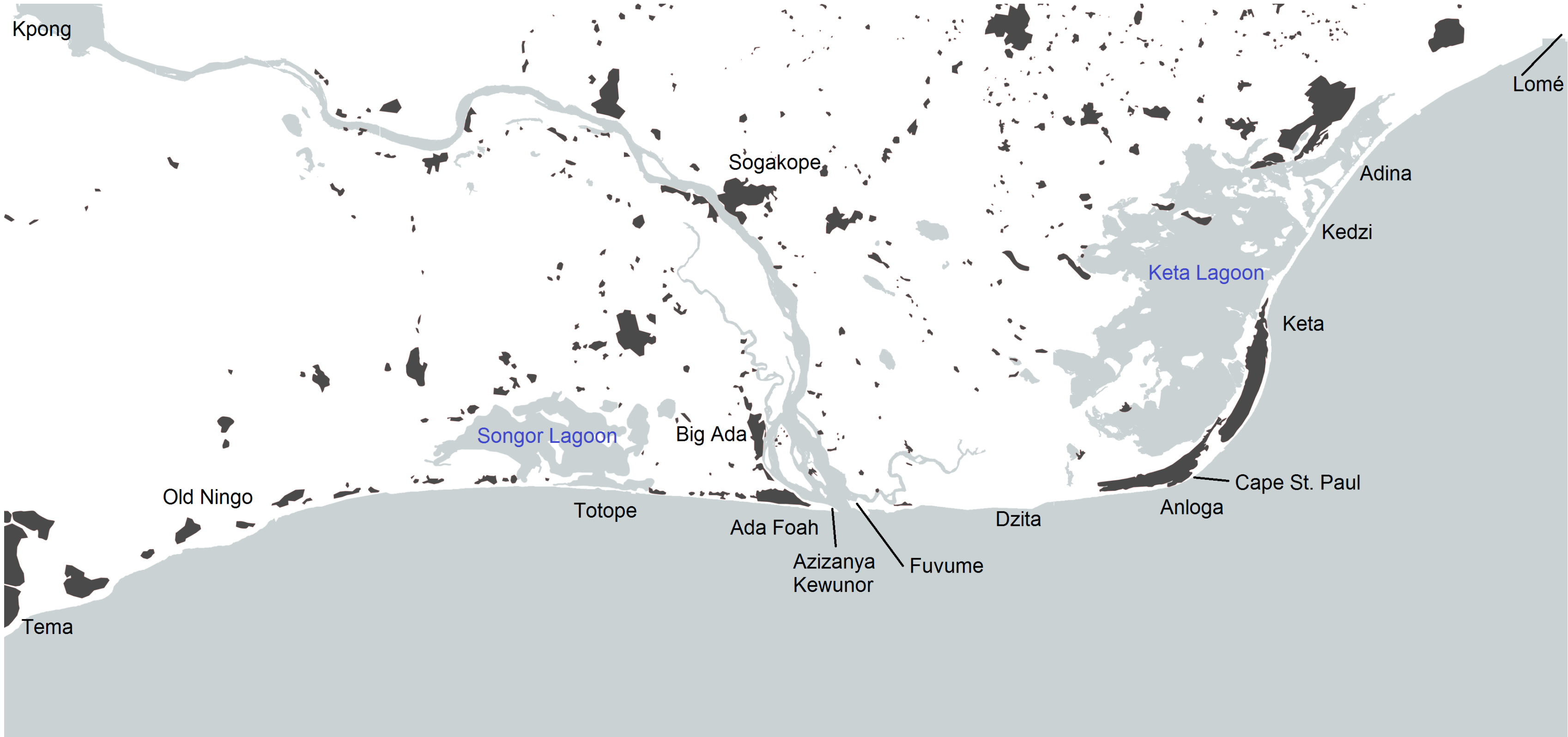

Figure B-1: Map showing the locations and names of villages mentioned in the report.

Appendix C

Process interactions

In this chapter it is aimed to present a simplified presentation of the interactions of subsystems in the Volta delta and their respective forcing. For instance beach morphology is mainly driven by wave hydrodynamics, but tides, and fluvial input also play a role.

The complex interactions regarding coastal morphology are schematised in Figure C-1.

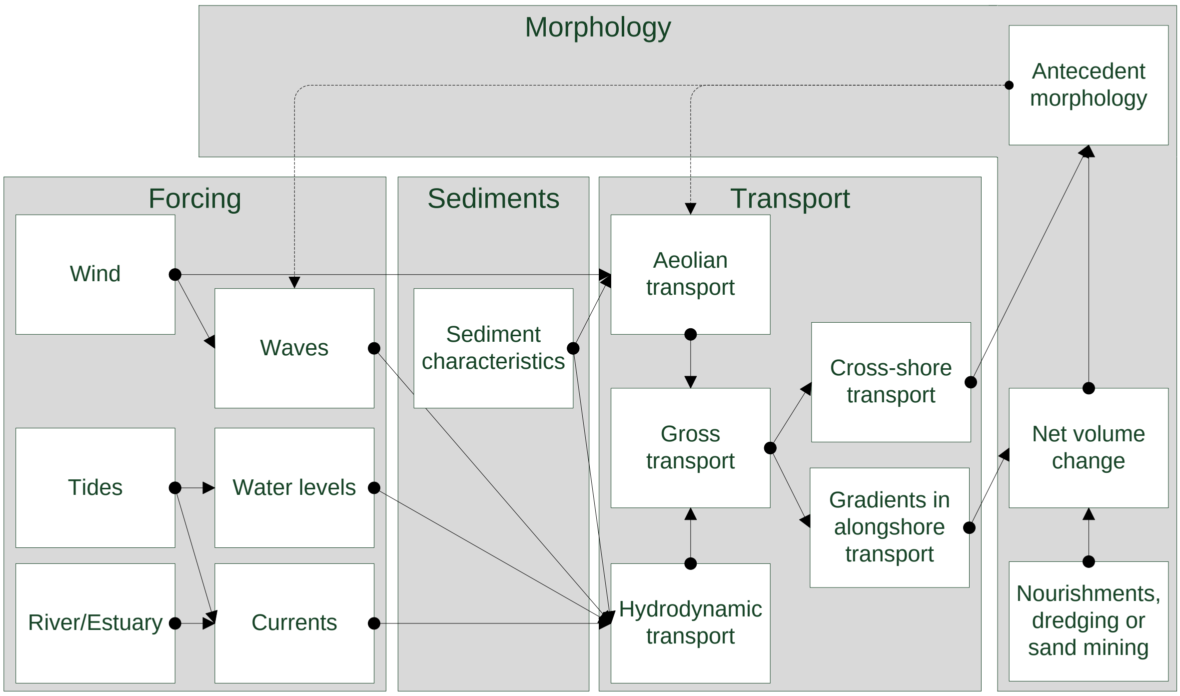

Figure C-1: Conceptual model of the processes influencing the coastal morphology, adapted from Roest (2017).

Hydrodynamics along the Ghanaian coast are dominated by the persisting SSW swell. Tidal and oceanic currents are mild. An exception is the immediate surrounding of the mouth of the Volta river.

The wave climate of the Bight of Benin causes one of the highest alongshore sediment transport rates known in the world. This littoral drift is uni-directional Eastbound along the entire coast of the Volta delta (and further up till Nigeria). Small perturbations in this drift will lead to enormous morphological responses.

Tidal currents in the estuary have a large effect on the bathymetry of the river mouth, see also Appendix A-2. The combination of large alongshore drift and the tidal in- and outflow cause the formation of a large spit from the west. Wave action pushes the spit towards the coast, while tidal currents maintain the channel connecting the river to the ocean. When at some point in time the spit breaks, the channel is no longer kept at depth by the tidal currents, and the 'loose' part of the spit is transported towards the coastline by wave interactions (overwash).

The shape of the river mouth also influences water levels and currents inside the estuary.

C-1 The erosion cascade or the consequences of blocking LST

The high alongshore transport rates found at the coast of the Volta delta are not necessarily a problem. If the amount of sediment arriving at a location equals the amount disappearing, no changes in the beach volume appear. However when a perturbation is made in the system, the gradients in transport become high and the morphological response is accordingly. Large erosion and accretion rates can be expected. Examples of perturbations are the construction of a groyne, port or breaching of a barrier.

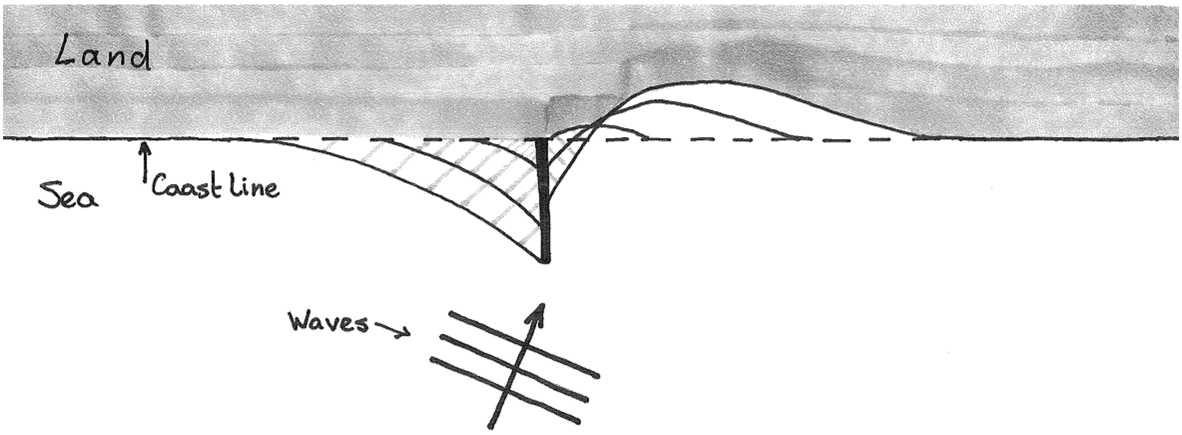

Figure C-2: Simplified morphological response on the construction of a single groyne. Up-drift (left) of the groyne the shoreline advances and aligns to the wave direction, down-drift erosion takes place. Eventually an equilibrium may be formed. The dashed line indicates the original shoreline position.

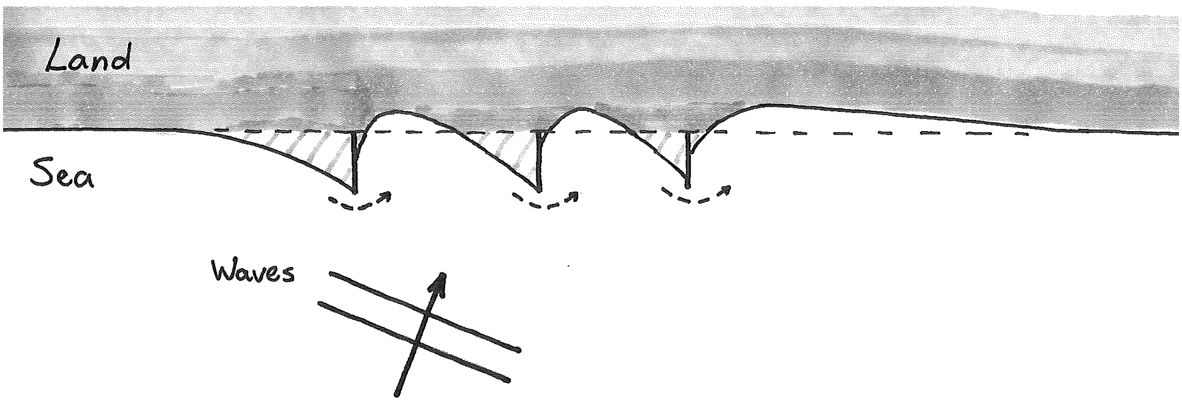

Figure C-3: Simplified morphological response to the construction of multiple groynes. On the up-drift side accretion takes place, on the down-drift side erosion. In between the groynes an equilibrium beach orientation may be formed. Bypassing of sediment along the groynes may occur when the up-drift input of sediments persists.

Nomenclature

D_{10}	Grain size for which 10% of the particles is finer [μm].
D_{50}	Median grain size diameter [μm].
D_{90}	Grain size for which 90% of the particles is finer [μm].
H_s	Significant wave height [m].
T	Wave period [s].
ϕ	Incident wave direction [°].
g	Gravitational acceleration [m/s^2].
h	Water depth [m]
accretion	Increase of the bed-level.
advance	Seaward displacement of isobaths/shoreline.
alongshore	Parallel to the coast.
alongshore transport	Sediment transport parallel to the coast.
bar	(Semi-)submerged ridge
barrier	Ridge of sand at the beach above high water level, created by waves.
bathymetry	topography of the sea-bed.
beach	part of the coast that is approximately between the low water level and the wave run-up level.
c	Wave celerity [m/s]
catchment area	Area receiving precipitation that drains into the same river.
clay	Mineral soil with a particle size smaller than 2μm.

coastal profile Cross-section of the coast, altitude versus distance.

Coriolis effect Inertial force with respect to a rotating frame of reference. Here: tendency of large scale (O(1000km)) flows to deflect to the right (left) on the northern (southern) hemisphere.

cross-shore Perpendicular to the coast.

cross-shore transport Sediment transport perpendicular to the coast

deep water In linear wave theory: waves are not influenced by the bottom ($h > 1/2 \cdot L$).

diffraction Bending of wave crests around obstructions (bars or breakwaters).

down-drift Relative position in the direction of the littoral drift.

dredging Removal of sediments from the sea floor, harbour, etc.

dune Row of hills above the high water level, created by wind transport.

erosion Decrease of the bed-level.

estuary Last part of a river before reaching the sea, with noticeable influence of the tides.

gravel Soil with a particle size larger than 2mm.

gross volume change Absolute sum of accretion and erosion.

groyne Stone dam perpendicular to the beach to decrease the longshore transport and divert currents.

groyne field Multiple groynes placed at some distance from each other alongshore.

gyre Large scale oceanic circulation. Flow patterns in the oceanic basins.

intertidal Between high- and low tide, usually the area that is flooded during high water, and dry during low water.

isobath Line of equal altitude (below MSL).

L Wave length [m]

lagoon Coastal body of water, usually shallow, separated from the sea by a barrier. It may be connected to the sea via a small inlet.

lake wide body of water, mostly stagnant.

littoral drift Alongshore sediment transport.

morphodynamics Changes in morphology.

morphology Form or shape of (in this case) the sea-bed, including the beach, channels etc.

net volume change Difference between accretion and erosion.

nourishment Supply of additional sediment to a beach to mitigate (future) erosion.

over-flow water-level induced flow over a structure (dike, barrier).

over-wash wave induced flow over a barrier or dike.

peat Organic soil, consisting of dead plant material.

refraction Change in wave direction due to gradients in propagation speed.

reservoir Artificial lake held back by a dam, usually for hydro power generation or irrigation.

retreat Landward displacement of isobaths/shoreline.

revetment Facing of stone to protect the beach or river bank from erosion by waves or currents.

river Stream of water, flowing from the high lands to the sea or ocean.

river basin See catchment area.

river mouth Place where a river flows into the sea.

run-up Level to which waves flow onto the beach.

sand Mineral soil with particle size between 63μm and 2mm.

sediment Collective of all geological deposits.

sediment transport (Quantification of) the displacement of sediments.

set-up Difference between the astronomical water level and measured water level, usually caused by strong wind.

shallow water In linear wave theory: waves are influenced by the bottom ($h < 1/20 \cdot L$).

shelf Submerged part of the continental plate, down to ca 200m below sea level.

shelf break Edge of the continental shelf, ca 200m below sea level.

shoreface Submerged part of the beach, between the surf-zone and the shelf break.

silt Mineral soil with a particle size between 2μm and 63μm.

slope local inclination of the surface.

stratigraphy Succession of geological (sediment) layers.

sub-aerial Below the air, permanently dry beach.

sub-aqueous Below water, permanently submerged beach.

surf-zone Area between the onset of breaking waves and wave run-up.

swell	Long waves, originating from grouped wind waves far away.
toe	Connection or transition of a construction (e.g. groyne, revetment, dike) to the subsoil at the lower end.
transect	Shore-normal line over which morphological suveys are measured.
up-drift	Relative position against the direction of the littoral drift.
wave celerity	Propagation speed of waves.
wave direction	Direction towards which waves propagate.
wave height	Height difference between the wave trough and top.
wave period	Time between the passage of two waves.
wave top	Highest point of a wave.
wave trough	Lowest point between two waves.
wind waves	Waves made by the wind.

List of Acronyms

ADCP	Acoustic Doppler Current Profiler
B.P.	Before present date
CST	Cross-shore Sediment Transport
DIMI	Delft Deltas Infrastructure and Mobility Initiative
GPS	Global Positioning System
HAWI	High-angle wave incidence
LAT	Lowest Astronomical Tide
LST	Longshore Sediment Transport
MHW	Mean High Water
MLW	Mean Low Water
MSL	Mean Sea Level
RSLR	Relative Sea Level Rise
RTK-GPS	Real-time kinematic GPS
SLR	Sea Level Rise

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