Analysis of two coastal lagoons in Ghana

an investigation of boundary conditions for the redesign of two lagoons along the Ghanaian coast

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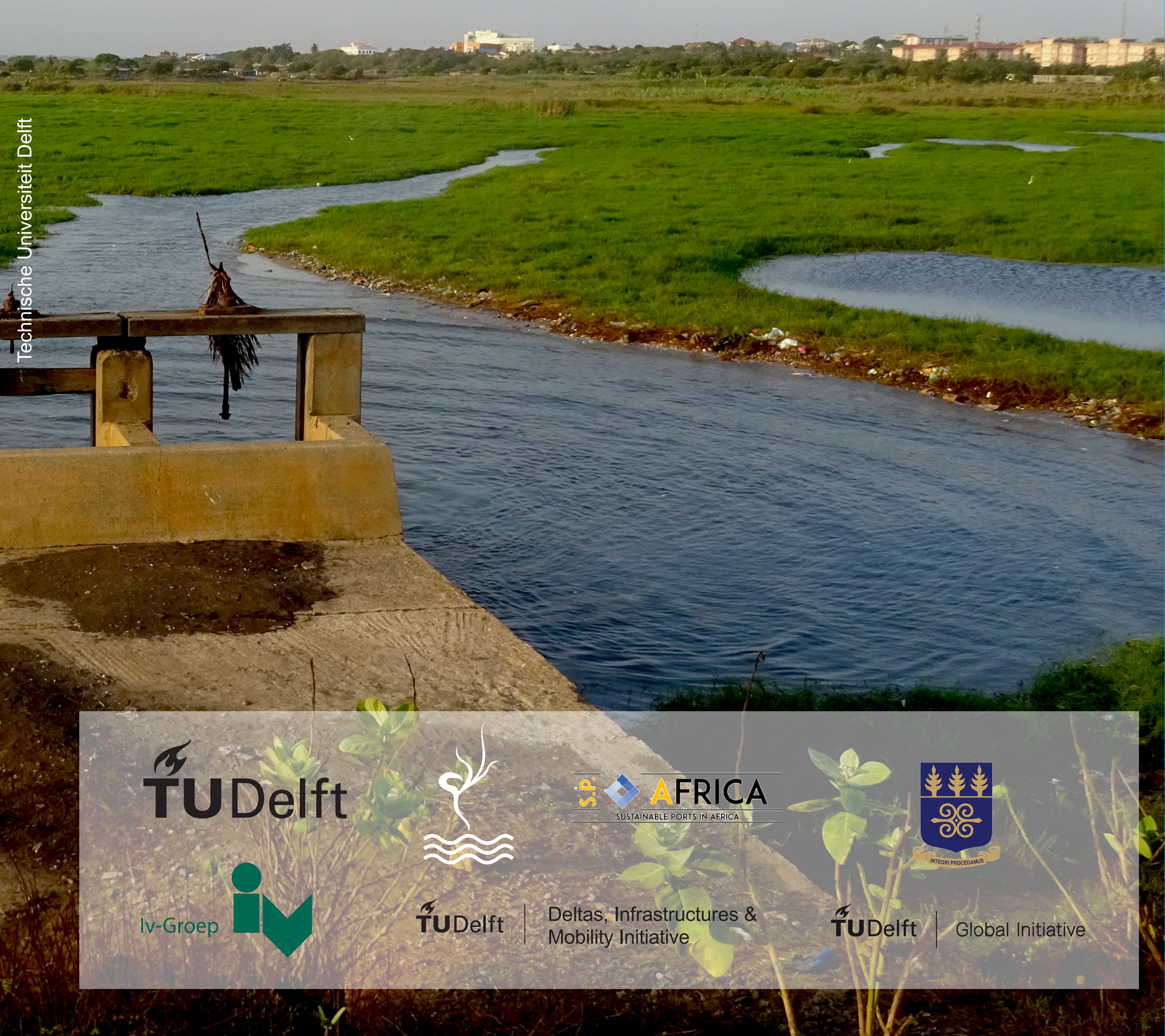

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by

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An electronic version of this report is available at `http://repository.tudelft.nl/`.

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Preface

Studying abroad in Ghana and doing this research as part of our masters was a great experience. As civil engineers in training, we wanted do a research project in Africa and were very pleased with obtaining this study.

Many thanks go out to Dr. Baukje Kothuis and prof. Jill Slinger in helping us find a well suited project. In Ghana, we were welcomed by prof. Kwasi Appeaning-Addo and dr. Edem Mahu. They made us feel at home right from the start of our time at the Department of Marine and Fisheries Sciences of the University of Ghana. They introduced us to students at the department who further helped us feel comfortable in Ghana. They helped us buy bicycles and took us to all the different food courts on campus. Therefore, many thanks go out to Michael for showing us around, and to Emmanuel and Philip-Neri Jayson-Quashigah for sharing their work space with us.

Within our project, we had a lot of help from Job Udo, who works for HKV and was commissioned by the World Bank to do a project to make Ghana flood safe. He linked us up with Obed Minkah of the Hydrological Services Department and with them, we worked on the flood safety models for the Sakumo lagoon.

As part of our project we analysed water samples in the laboratory of the university. We received a lot of help from Charles Mario Boateng and Kofi Anyan in analysing water and soil samples. We express our gratitude to them for helping us out in the lab.

Furthermore, we would like to thank everyone who took the time answering our many questions and for providing us with data.

Robert Jan Labeur, Roland Abspoel and Thom Bogaard are thanked for their work as supervisors from our different master tracks.

Niels van Leeuwen

Lars Pije

Ascha Simons

Chris Wauben

Delft, May 2018

Abstract

Two polluted Ghanaian lagoons are investigated and possible engineering solutions are suggested and researched.

The first lagoon is the Sakumo lagoon, located between Accra and Tema. This lagoon is connected to the sea through a small culvert, which enables a limited amount of water exchange. Since a few years, fishermen have been unable to catch fish in this lagoon, because of invasive plants restraining them from entering the basin. The siltation rate is high due to increasing friction because of these plants and limited sediment outflow through the small culvert. Furthermore, the water quality in the lagoon is poor. An overland flow model and a mixing model are used to evaluate the effects of a change in layout of the lagoon mouth. From this, it follows that a larger connection to the sea is beneficial to the water quality while still maintaining flood safety. However, decisions on the redesign of this lagoon mouth should be made with close regard to stakeholder interests.

The second lagoon is the Klottey lagoon, located in the city centre of Accra. The surroundings of this lagoon are planned to become an area of tourism. Neighbouring the lagoon, a new fishing harbour is planned. The water quality in this lagoon is poor and its water flows along the shore of Accra. The water quality in and near the lagoon is investigated with the development plans of the area in mind. Furthermore, the shoreline response as a result of these interventions is assessed.

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1 Introduction

1.1. Background of study

This report is made as part of the Master of Civil Engineering at the Delft University of Technology, The Netherlands. In the master program, students have the choice to do a Multidisciplinary Project. In this course, with course code CIE4061-09, students from various disciplines combine their knowledge to tackle a self-defined problem. This report is a product of this course.

1.2. Project team

Figure 1.1: The project team. From left to right: Niels van Leeuwen, Ascha Simons, Chris Wauben and Lars Pije

The project team consists of four Civil Engineering master students. Each of them specialises in a different subject. A small overview of the project members and their background is given below.

- Niels van Leeuwen is following the Master of Water Management and is specialising in Water Resources.
- Lars Pije is following the Master of Structural Engineering where he is specialising in Structural Mechanics.
- Ascha Simons is following the Master of Hydraulic Engineering where she is specialising in Environmental Fluid Mechanics.

- Chris Wauben is following the Master of Hydraulic Engineering where he is specialising in Hydraulic Structures and Flood Risk.

1.3. Case

The project will focus on two lagoons on the West-African coast. They are located in the Greater Accra Region in Ghana.

(a) Greater Accra Region in Ghana

(b) Locations of the Sakumo and Klottey lagoons

Figure 1.2: Overview

The first lagoon that will be assessed is the Sakumo lagoon. This lagoon is located between the Ghanaian capital of Accra and the neighbouring port city of Tema. Currently, the lagoon is in a bad state regarding its water quality. The port of Tema is currently being expanded and is used as a pilot for NWO-UDW's "Integrated and Sustainable Port Development in Ghana" project. Part of the Sustainable Port Development project is to provide added value to the surrounding area. This report assesses the current state of the lagoon and investigates possible future improvements to its mouth in order to enhance the quality of the lagoon.

Secondly, the Klottey lagoon area is investigated. This lagoon is located on the south shore in the middle of Accra. The lagoon and its surroundings are heavily polluted. West of the lagoon, a touristic area is being developed; the Marine Drive project. Therefore, the need has arisen to look into the state of the neighbouring lagoon. This report assesses the current state of the lagoon and its surroundings. It also investigates the current and future impact of the lagoon and its pollution on the Marine Drive Project site.

The report can be seen as an assessment of two coastal lagoons in Ghana, investigating their current state and how alterations may impact the lagoons and their surroundings. Coastal lagoons are often complex systems where water quality can be heavily impacted by changes in the hydraulic system. This hydraulic system in its turn is influenced by the presence of man-made structures. Because these features all influence each other, it is necessary to view this problem from multiple different angles. That is why this project calls for a multidisciplinairy approach, so that the knowledge of all these fields is brought together to tackle the problem.

Since this report focusses on the assessment of two separate lagoons, each with its own specific focus, the two parts of this report can each be viewed individually.

I

Sakumo Lagoon

2
Introduction

In the first part of this report, the Sakumo lagoon will be assessed. In this introduction, a brief overview of the lagoon is given, followed by the background of study. This is followed by the problem statement and the structure of this part of the report.

2.1. Overview

Figure 2.1: Overview of the location of the Sakumo Lagoon

The Sakumo lagoon lies on the West-African coast in between the Ghanaian capital of Accra and the neighbouring port city of Tema. Its main basin is located at coordinates 05°36’59”N, 0°01’59”W. The lagoon varies in size depending on the season, at around 1 km^2 in the dry season and 4 km^2 in the wet season. Water depths rarely exceed 1.0 m and also vary depending on the season.

Various names are used for the lagoon. The original name is the Sakumo Lagoon. This name refers to a locally worshipped God. Its shrine is also located in the lagoon. Since another Ghanaian lagoon is also called the Sakumo Lagoon, it was decided to number them. The lagoon is therefore also called the Sakumo II Lagoon or Sakumo 2 Lagoon, with the Sakumo 1 Lagoon being the Densu Delta to the west of Accra. West of the Sakumo 2 Lagoon, the Sakumono fishing village is located. The lagoon is sometimes also named the Sakumono Lagoon after this fishing village. However, Sakumo Lagoon will be the name used for this lagoon in this report. Please note that it can be used interchangeably with Sakumono-, Sakumo 2- or Sakumo II Lagoon. These various names of the lagoon should be kept in mind when searching for historical literature about the lagoon.

The lagoon used to be a semi-closed lagoon. For most of the year, it was blocked by a sand bar at its mouth and there was no interaction with the sea. After heavy rainfall events, the water broke through the sand bar, flushing the lagoon. In 1953, the Accra-Tema road was constructed over the mouth of the lagoon. A culvert was built underneath the road, permanently connecting the lagoon with the sea. For more details on the history of the hydrology and structures in the lagoon, see chapter 4.

The port of Tema is the largest port of Ghana and attracts a lot of industry. The amount of jobs generated by the industrial growth has increased the housing demand. As houses are not readily available, people have started to build in places where it is not allowed, like in the floodplains of the Sakumo lagoon. This encroachment causes some houses to flood during the wet season.

Some local rules, locally referred to as taboos, exist for fishing in the lagoon. The lagoon is closed for fishing from around October/November to March/April and fishing is prohibited every Friday before noon. The use of canoes is prohibited, and so is the use of draw nets with mesh sizes under 2.5 cm. However, these taboos do not have any legal status and some reports suggest that the local knowledge on these taboos is minimal (Agbemehia, 2014) and the compliance to these taboos is something of the past (Entsua-Mensah et al., 2000).

2.2. Background of study

Due to the population growth in Africa, new ports are needed to fulfil the transportation and trade demands. New ports have to be developed and designed, preferably in a way in which environmental, economic and public benefits are balanced. In order to improve sustainable port development, NWO-UDW initiated the project ”Integrated and Sustainable Port Development in Ghana”. This project aims to develop a generic framework for designing sustainable ports in Africa. The Ghanaian port of Tema has been selected as a pilot project.

The Sakumo Lagoon is located near the port of Tema. The lagoon is currently in a bad state regarding water quality. Residents, factories and agricultural businesses use the streams leading to the lagoon and the lagoon itself as a waste drain. The culvert connecting the lagoon with the sea provides minimal flushing. This, in combination with increasing population, causes pollution levels to rise. The lagoon has also experienced severe sedimentation over the past years.

Part of the Sustainable Port Development project is to provide added value to the surrounding area. The Accra-Tema road, which is a coastal road running over the mouth of the lagoon, might have to be altered due to the port’s expansion and subsequent increase in infrastructure demand. The redesign can be conducted in such a way that it increases the quality of the lagoon. This report investigates the possibilities of improving the lagoon, as a part of the expansion of the port of Tema, focussing on the mouth and the interaction of the lagoon with the sea.

2.3. Problem statement

The central question that will be answered in this report is:

> *How can the mouth of the Sakumo lagoon be redesigned given the preference for a more natural, safe and healthy lagoon system?*

In order to answer this question, a more detailed understanding of the lagoon system is needed. The following sub-questions will need to be answered as well:

1. *What structures are situated in the mouth of the lagoon and what is their function and state?*
2. *What are the governing hydraulic processes of the lagoon and how can these be modelled?*
3. *What is the current state of the lagoon regarding water quality?*
4. *Which stakeholders are of importance to the Sakumo lagoon and how does that affect the decision-making process?*
5. *What is the response of the system to changes to the mouth design?*

2.4. Outline

This report will be structured as follows. First, in chapter 3, the structures that are situated in the mouth of the lagoon will be analysed. Then, in chapter 4, the hydraulic system of the lagoon will be discussed, with an overland flow model in chapter 5 and a mixing model in chapter 6. The water quality of the lagoon will be assessed in chapter 7, after which a stakeholder analysis will be provided in chapter 8. Finally, in chapter 9, a few design alternatives for the mouth of the lagoon will be presented, with some concluding remarks and recommendations in chapter 10.

3
Structures

A brief overview of the structures in the mouth of the Sakumo lagoon will be given, as well a qualitative analysis on the current state of the structures. The chapter will be concluded with a brief explanation of the effects of seawater on concrete structures.

3.1. Overview existing structures

Two concrete structures are present in the mouth of the Sakumo Lagoon. Together, they regulate the rate at which water can flow in and out of the lagoon. Both of them are located southeast of the main basin, near the harbour of Tema. There is a culvert and a storm drain, as shown in figure 3.1.

Figure 3.1: Structures in the mouth of the Sakumo Lagoon

3.1.1. Culvert

The culvert, built in 1953, is a concrete structure made up of two pipes with a diameter of 6 feet (1.82 m). It is constructed through the embankment, underneath the coastal road. At the seaside, the pipes curve off to the east to limit the inflow of seawater. At the lagoon-side of the embankment, there used to be two sluice gates (one for each pipe) to regulate the outflow of water from the lagoon. These sluice gates are no longer operational, which has led to a permanently open connection between the lagoon and the sea through the culvert.

At low tide, the culvert structure is completely emerged from the sea, with only the occasional wave high enough to reach the structure. Because the water level in the lagoon is usually higher than the bottom level of the culvert pipes, water can freely flow out of the lagoon at low tide. During high tide, the

Figure 3.2: Culvert structure, seen from the lagoon side

culvert is partly submerged, with some waves even overtopping the structure. This means the entire seaward part of the structure is exposed to direct seawater and wave action.

3.1.2. Storm drain

Figure 3.3: Storm drain, seen from the sea side

In 1997, after a big flood, it became clear that the culvert alone was not sufficient to handle the rainfall runoff from the lagoon (W. Ametefe, pers. comm.). Therefore, a storm drain was constructed some 20 m east of the original culvert structure. This storm drain consists of four concrete pipes with a diameter of 1.40 m, constructed about one meter higher than the culvert and presumably with a slight descending slope towards the sea. This means water will only flow through the storm drain out of the lagoon into the sea with extremely high water in the lagoon.

Because of its elevation, the storm drain is less prone to interaction with seawater. For the greater part of the tidal cycle, the storm drain is completely free from seawater interaction. However, at spring tide some waves reach the structure. Therefore, the storm drain is occasionally directly exposed to sea water and wave action. A toe was installed to further limit this exposure, as can be seen in figure 3.3. The toe is made of cemented tiles of natural stone, presumably because this stone is more resistant to erosion than concrete. Altogether, this makes for a lot less exposure to seawater than the culvert.

3.2. Current state of the structures

As mentioned in the previous section, both structures are a few decades old. They show varying degrees of concrete degradation. The extent and the possible causes of this degradation will be discussed in this section.

3.2.1. Culvert

The culvert has been exposed to direct wave action for 65 years and shows severe signs of deterioration. At the entire seaside of the structure, the top layer of the concrete has been eroded, leaving the bare aggregate exposed. The aggregate is notably coarse, up to 50 mm from what can be seen. In some spots large chunks of concrete have broken off. Furthermore, the bottom part of the right outlet in figure 3.4b is completely eroded, exposing the rocks underneath the culvert.

Large cracks run along the entire structure, as can be seen in figure 3.4a. Most of them are straight and run around or along the entire culvert structure. This suggests that the cracks have formed along the seams of the structure.

(a) Overview of the sea side part (b) Seaside opening

Figure 3.4: Culvert structure

At the lagoon side, the culvert structure looks much better. There is one large crack visible around the structure, probably at an old seam. Furthermore, some smaller cracks can be seen at the top of the structure. As mentioned before, there used to be two sluice gates at the lagoon side of the structure, but they are no longer present. They once served the purpose of closing off the lagoon in the dry season, retaining a certain water level for fishery (W. Ametefe, pers. comm.). It is unclear why they have not been repaired or re-installed.

3.2.2. Storm drain

The storm drain is in a much better shape than the culvert. This can mainly be attributed to its age, but also since it is not as directly exposed to the wave action as the culvert. Nevertheless, the storm drain also shows some signs of concrete degradation. There are multiple noticeable brown spots on the surface, indicating corrosion of the reinforcement. This is also visible in the top right corner facing the structure from the sea side. There, a corner has broken off, exposing the rusted reinforcement bar underneath.

3.2.3. Causes of deterioration

In marine environments, concrete is exposed to the corrosive and erosive effects of seawater. The main threats are rebar erosion due to chloride attack and erosion due to flow and wave action.

Chloride attack (corrosion) Under normal conditions, steel reinforcement in concrete is protected against further erosion by a protective layer of corrosion that naturally covers reinforcement steel (Neville, 1995). However, chloride ions disrupt this protective corrosion layer and cause the steel to corrode more if oxygen is available. This has two negative consequences. Firstly, it reduces the

(a) Cracked concrete (b) Eroded concrete

Figure 3.5: Concrete degradation of the culvert structure

effective area of the steel, weakening the reinforcement. Secondly, the rust takes up more volume than the original steel, leading to cracks in the surrounding concrete.

Seawater naturally contains high concentrations of chloride ions. When seawater penetrates the pores of the concrete, the chloride ions can react with the protective oxidation layer of the steel. If sufficient oxygen is available, the oxidation process will continue, damaging the concrete. The availability of oxygen is the reason why submerged concrete is less prone to chloride attack than concrete in the tidal, splash and spray zones. The latter of which is exposed to more oxygen from the air.

Erosion Apart from being corrosive, seawater can also contribute to erosion. Wind waves crashing on the surface of concrete will gradually knock off small pieces of mortar, exposing the coarse aggregate underneath. The sediment carried by these wind waves amplify this effect. This process is called abrasion erosion (Liu et al., 2006). Given enough time, this abrasion erosion can eat away large parts of the concrete. This leaves reinforcement bars exposed to direct seawater interaction, which in turn leads to an acceleration of corrosion.

Fulfilled lifespan All structures are designed and built to function during a certain time span. Usually, the design lifetime is 50 years. Assuming that the culvert structure was originally built with this lifespan in mind, it is not surprising that it shows signs of deterioration after 65 years of service.

3.3. Conclusions and recommendations

The culvert has exceeded its intended lifespan. Aesthetically, it is in bad condition. Large cracks, large chunks of broken off concrete, strong signs of corroded reinforcement and of course the faulty sluice gates make for a fragile looking structure. It is hard to say if it is structurally unsafe. Further investigation could prove useful in order to make a definitive statement on the structural integrity of the structure. However, its age and the fact that it is visibly in poor condition might be enough reason to replace it entirely.

The storm drain is still in reasonably good condition, showing only minor signs of degradation. Monitoring the degradation rate of this structure would be wise. Replacement of this structure is, as opposed to the culvert, not urgent.

In order to protect new structures against seawater, some measures can be taken. For instance, a protective coating could be used in order to limit seawater intrusion (Schueremans et al., 2007). Another viable option is to use a coarser aggregate in the concrete, since concrete with coarser aggregates is less susceptible to erosion (Liu et al., 2006).

4 Hydraulic system

An understanding of the hydraulic processes in and around the lagoon is necessary for making predictions of the system response to changes. Therefore, the history of the lagoon system and the dominant hydraulic processes will be discussed in this chapter. These processes influence the amount of mixing and flushing in the lagoon, for which some estimates will be made. Mixing and flushing are important for the movement of pollutants, influencing the water quality of the lagoon.

4.1. History

According to the definition of Boughey (1957), the Sakumo lagoon used to be a closed lagoon. This means that it was separated from the sea by a sand dune (Pauly, 1975), with no seawater intrusion for most of the year. After a large rainfall event, water levels in the lagoon would rise and saturate the sand bar separating the lagoon from the sea. When water levels were high enough, a breach was formed connecting the lagoon to the sea for some time. When the amount of rainfall was no longer sufficient to maintain the connection with the sea, the sand bar would be formed again. The cycle would then repeat itself. It was confirmed that this was indeed the way this lagoon functioned in personal communication (W. Ametefe, pers. comm., Local fishermen, pers. comm.)There are also other closed lagoons along the Ghanaian coast that behave this way, or have behaved this way in the past. An example is the Mukwe Lagoon located nearby (Kwei, 1977).

In 1953, a culvert and sluice structure was built, permanently connecting the lagoon to the sea through the sand dune (Ntiamoa-Baidu and Gordon, 1991). It is the structure on the right in figure 4.1b. The culvert was built to enable the construction of the Accra-Tema road along the coast. This road runs over the sand dune along with a rusty railroad track, see figure 4.1a. The culvert prevents unpredicted flooding of the road (Pauly, 1975) and breaching of the embankment.

The culvert consists of two 70 m long concrete tubes with a diameter of 1.83 m or 6 ft (Kwei, 1977; Global Environment Facility, 1992) The southern end of the culvert makes a slight turn to the east, to prevent sea water from from hindering outflow of the lagoon after a heavy rainfall event (W. Ametefe, pers. comm.). The outflow from the culvert is then directed towards the east, which is the dominant direction of the coastal current (Roest, 2018). Waves arriving in shore-normal direction are unable to intrude the culvert pipes, thereby increasing the capacity of outflow during a rainfall event (W. Ametefe, pers. comm.). The culvert protruding from the embankment in seaward direction can be seen in figure 4.2.

On the lagoon side of the culvert, sluice gates were constructed in order to regulate the water exchange between the lagoon with and sea (see figure 4.3a). They were once used to retain a certain water level during the dry season (W. Ametefe, pers. comm.). Presently, in 2018, the sluice gates are not functioning any more. Ntiamoa-Baidu and Gordon (1991) reads that the sluice gates were not functioning in 1991 and mr. Ametefe confirms that they have been out of order for more than 30 years.

For a more detailed description of the culvert, see section 3.1.1.

There was a large rainfall event in 1997, flooding the surroundings of the lagoon (GhanaWeb, 1997) (W. Ametefe, pers. comm., Local fishermen, pers. comm., C. Amankwah, pers. comm.). The culvert did not have sufficient capacity to discharge the water from the lagoon quickly enough. That is why, in

(a) Coastal road and rail road track

(b) Storm drain (left) and culvert (right) on the lagoon side

Figure 4.1: View of the embankment separating the lagoon from the sea

(a) Culvert structure protruding from the embankment

(b) Endings of the pipes, directed to the east

Figure 4.2: Sea side of the culvert

the same year, a storm drain was constructed 20 m east of the existing culvert to prevent future floods. The storm drain consists of four tubes with a diameter of 1.4 m. Their elevation is about one meter higher than the original culvert. It can be seen in figure 4.4. The tubes seem to be built at an incline, with a lower bottom level at the sea side in order to increase outflow capacity (personal observation). This was confirmed by (C. Amankwah, pers. comm.) but remained unclear in conversation with (W. Ametefe, pers. comm.), because the original design drawings could not be retrieved. Since the construction of the storm drain, there has not been a flooding as severe as in 1997 (C. Amankwah, pers. comm.).

For a more detailed description of the storm drain, see section 3.1.2.

4.2. Area and system

A general overview of the area and hydraulic system of the Sakumo lagoon will be provided in this section. The dimensions of the lagoon and its catchment will be given, along with information on the climate. From the rainfall in the area, some estimates will be given on the inflows in the lagoon.

4.2.1. Catchment area

The catchment area of the Sakumo Lagoon varies greatly in literature. Reported findings are 222 km^2, 242 km^2, 276 km^2 and 127 km^2 (Ntiamoa-Baidu, 1991; Global Environment Facility, 1992; Agyepong, 1999; van Stiphout, 2002). Measuring from a Digital Elevation Model (DEM) based on elevations provided by the Lands Commission, the catchment area measures approximately 286 km^2. It ranges about

(a) Lagoon side of the culvert

(b) Stream running towards the culvert

Figure 4.3: Overview of the mouth area of the lagoon

(a) Lagoon side

(b) Sea side

Figure 4.4: Storm drain

30 km from north to south and 20 km from east to west.

4.2.2. Lagoon area

The size of the lagoon area varies between wet and dry season. Different sizes are mentioned in the various literature. Estimates of the size of the lagoon vary dramatically. Values mentioned range from 0.5 km^2 in the dry season to 10 km^2 in the wet season (Pauly, 1975; Kwei, 1977; Gordon, 1987; Ntiamoa-Baidu, 1991; Global Environment Facility, 1992; van Stiphout, 2002; Nonterah et al., 2015). According to various stakeholders, the area of the basin has decreased rapidly in the past years (C. Amankwah, pers. comm., Mr. De Graft-Johnson, pers. comm.). This reduction has mainly been ascribed to siltation.

There has been an increase in siltation rate in the past ten years (R. Asmah, pers. comm., Mr. De Graft-Johnson, pers. comm.). Reportedly, the cause of this increase is an introduction of vegetation that was not previously found in the Sakumo Lagoon. This new type of vegetation is a strong reed that gradually replaces the native water lettuce found in the lagoon. However, unlike water lettuce, the new vegetation does not die in the dry season, increasing the sediment retention capacity of the lagoon.

4.2.3. Lagoon volume

The mean water depth in the lagoon is reportedly around 80 cm in the wet season (van Stiphout, 2002) and 50 cm in the dry season (Pauly, 1975). With the corresponding areas of around 4 km^2 and 1 km^2 respectively, this makes for a lagoon volume of 3.26×10^6 m^3 in the wet season and 0.5×10^6 m^3 in the dry season.

4.2.4. Climate and rainfall

The Sakumo lagoon is located in a coastal savannah vegetation zone. It experiences a bimodal rainfall pattern with an annual average of approximately 800 mm (Nonterah et al., 2015). Data received from the Ghana Meteorological Agency (GMET) shows a mean annual precipitation of 714 mm at the Tema measuring station, the measuring station closest to the Sakumo lagoon. This mean precipitation is based on daily data from 1961 to 2015. The yearly rainfall for this period is shown in figure 4.5. It can be seen that yearly rainfall amounts range from 329 mm per year to 1656 mm per year.

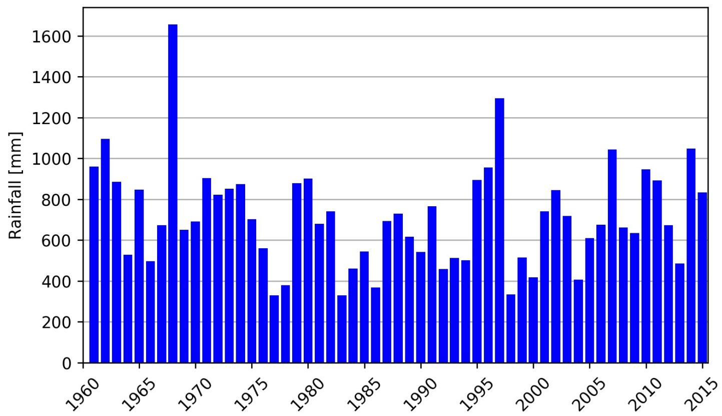


Figure 4.5: Yearly rainfall in Tema for the period 1961-2015

The Sakumo lagoon is located between Accra and Tema. To analyse the spatial differences of the rainfall in the area, data from the Accra airport measuring station is analysed as well. Figure 4.6 shows the yearly rainfall for the Accra airport measuring station. Rainfall amounts range from 333 mm to 1413 mm per year, with an average of 805 mm per year.

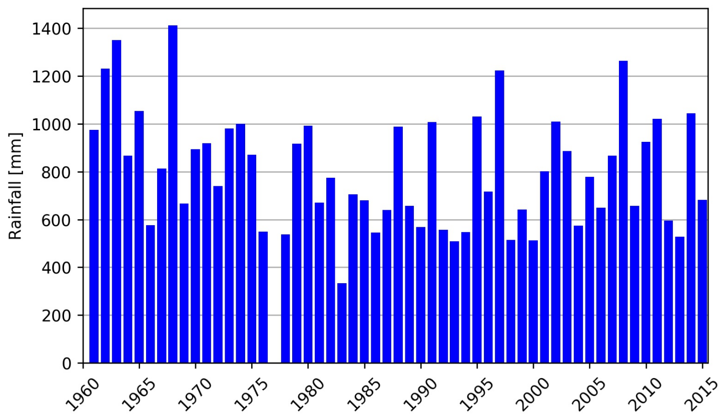


Figure 4.6: Yearly rainfall in Accra for the period 1961-2015 (data for 1977 is missing)

In figure 4.7 the mean monthly rainfall is shown based on data from 1961 to 2015 for both the Accra and Tema measuring stations. The main dry season extends from November to March, with a minor dry season around August.

The mean monthly precipitation rates differ between the Accra en Tema measuring stations, as can be seen in figure 4.7. These measuring stations are approximately 20 km apart. The precipitation in Accra is generally a few mm higher with June having the largest difference of 26 mm. The difference in precipitation between the measuring stations has to be taken into account when interpreting the results of this report. The Sakumo catchment stretches 30 km from north to south, more than the distance between the two measuring stations. So precipitation most likely differs within the catchment as well.

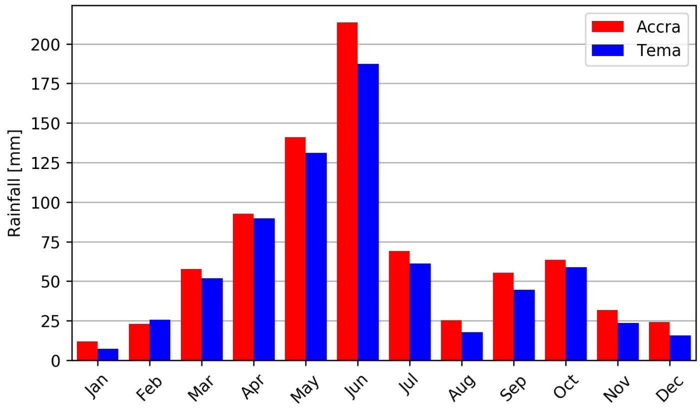


Figure 4.7: Mean monthly rainfall in Tema and Accra based on daily measurements in the period 1961-2015

Normal and extreme conditions

Normal conditions Because of the strong seasonality of the rainfall events, the normal conditions are split up into dry- and wet season values. For a normal dry season rainfall event, the mean value of all rainfall events in the dry season was used to provide an estimate of 11 mm in 24 hours. The mean total rainfall during the dry season is 58 mm. For a wet season rainfall event, the median value of the maximum yearly rainfall event is used to provide an estimate of 73 mm in 24 hours. For an elaboration on the calculation of these values, see appendix C.

Extreme conditions An extreme rainfall event is most likely to occur in the wet season and is estimated for several return periods in appendix C. With the structure designed for a lifetime of 50 years with a probability of failure $P_f = 10\%$ in this lifetime, this results in a rainfall event of 233 mm.

4.2.5. Inflow

Several small rivers feed water into the lagoon. These are, from west to east, the Onukpawahe, Mamahuma, Dzorwulu and Gbagbla-Ankonu, shown in figure 4.8. The first pair and the second pair join together a few kilometres upstream of the main basin. Since people are moving into the floodplains of the lagoon, the consequences of flooding are becoming increasingly severe. Therefore, part of the Dzorwulu/Gbagbla-Ankonu stream was channelised by the Hydrological Services Department (HSD) in 2013, to facilitate water flow and prevent flooding of the nearby houses. HSD is continuing the channelisation of the other streams in an effort to improve the flood safety of the area (O. Minkah, pers. comm.).

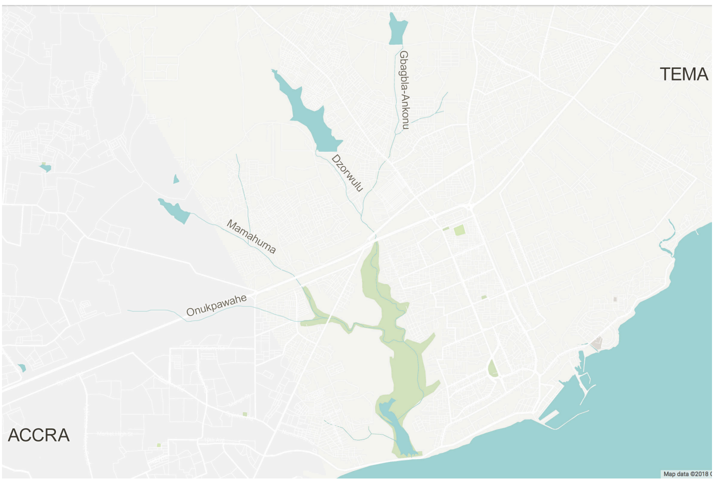


Figure 4.8: Rivers flowing into the Sakumo Lagoon

4.2.6. Discharge

The normal and extreme rainfall events described in section 4.2.4 produce discharges into the lagoon. These discharges are estimated for both normal and extreme conditions. The estimates are based on the total volume of water that precipitates onto the catchment of the Sakumo lagoon, under the assumption that not all water flows into the lagoon. Part of the precipitation is lost to surface storage, interception, infiltration, evaporation and transpiration. These factors all decrease the amount of water flowing into the lagoon.

The percentage of precipitation that results in runoff is difficult to determine. It is dependent on soil type, vegetation, catchment size and slope. Values are therefore not easily obtained and are usually based on field studies on a particular area. As an initial guess, the percentage of precipitation that will result in runoff is estimated at 50 %.

With the catchment area of 286 km^2 mentioned above and the analysis of normal and extreme rainfall events, an estimation of the order of magnitude of the inflow of water into the lagoon is made.

Area reduction factor The precipitation measurements of the Tema measuring station are point measurements. Since the amount of precipitation on an area is, on average, less than the amount measured on one point, an Area Reduction Factor (ARF) is necessary to account for this difference. The ARF used for the catchment of the Sakumo Lagoon is based on the comparison of point measurements and satellite data on precipitation. It is calculated using the equation found by HKV, a Dutch consulting company, for precipitation in the Greater Accra Region. For a catchment area of 286 km^2, the ARF is 0.75. This value will be multiplied with the point-measured effective precipitation in order to estimate the total precipitation on the area. More details on the ARF can be found in appendix D.

Intensity The daily precipitation values are not uniformly distributed over a day: every rainfall event has a peak. During or directly after this peak, the largest discharges into the lagoon are found. An estimation is made on the percentage of the precipitation that falls in a one-hour period. It is based on the intensity-duration-frequency (IDF) curve of the Tema measuring station

A return period is chosen, after which the 24-hour rainfall event is calculated based on the fitted probabilistic distribution. This daily rainfall value is compared with the 1-hour rainfall value for the same return period, extracted from the IDF curve. This comparison shows that around 50 % of the total daily precipitation is concentrated in a one-hour block. This value will be used to estimate the peak discharge during a rainfall event.

Normal and extreme conditions The discharges for the normal and extreme conditions are provided in table 4.1.

Table 4.1: Discharges for various rainfall events

Normal conditions		precipitation [mm/day]	runoff [m^3/s]	peak runoff [m^3/s]
	dry season average	0.54	0.67*	-
	dry season event	11	14*	164
	wet season event	73	91	1087
Extreme conditions	return period	precipitation [mm]	runoff [m^3/s]	peak runoff [m^3/s]
	5 years	110	137	1639
	10 years	129	160	1922
	25 years	154	191	2294
	100 years	191	237	2845
$P_f = 10\%$	475 years	233	289	3471
$P_f = 5\%$	975 years	253	314	3769
$P_f = 1\%$	4975 years	297	369	4424

* This is most likely an over-estimation.

As can be seen in table 4.1, the average dry season discharge into the lagoon would be 0.67 m^3/s, or 58×10^3 m^3/day with this calculation. However, in case of small rainfall events the percentage of precipitation resulting in runoff is much smaller than in case of large rainfall events. This is because the infiltration capacity of the soil, which is initially unsaturated, drastically decreases with time. Especially for large catchment areas, the runoff is minimal for small rainfall events. The discharges provided for the dry season rainfall events will therefore be overestimated. This is confirmed by comparing the daily average dry season discharge with the total lagoon volume in the dry season, 1.5×10^6 m^3. Using the assumptions explained above, the daily dry season discharge accounts for almost 4 % of the total lagoon volume. This is highly unlikely, so that an estimation provided by van Stiphout (2002) will be used for further calculations. The average runoff in a year is estimated to be 0.26 m^3/s. Because it follows from the rainfall data that about 8% of the total yearly rainfall falls during the dry season, the yearly average runoff value is split up into a dry- and a wet season value accordingly. This leads to 0.074 m^3/s (or 6.4×10^3 m^3/day) for the dry season and 0.341 m^3/s (or 29.5×10^3 m^3/day) for the wet season.

4.2.7. Upstream dams

Several irrigation dams are located in the upstream region of the Sakumo Lagoon. These dams are located in the Mamahuma, Dzorwulu and Gbagbla-Ankonu streams. Due to intensifying agriculture, increasing amounts of water are used for irrigation decreasing the amount of precipitation finding its way to the downstream lagoon (W. Ametefe, pers. comm.). Details on the management, discharges and heights of these irrigation dams remain unknown.

4.3. Coastal system

The sea climate is quite temperate. That is why flood related problems in and around the lagoon originate mostly from heavy rainfall events in combination with the culverts preventing water from flowing freely out of the lagoon. Nevertheless, understanding of the basic processes at the mouth of the lagoon is necessary for the redesign of the lagoon mouth. Information on wind waves, ocean currents and tide is gathered and presented in this section.

4.3.1. Wind waves

Representative values for the wind waves were calculated from the CAWCR hindcast model (Durrant et al., 2013). This dataset provides hourly significant wave heights, peak periods and wave directions from 1979-2010 based on recorded climate data. The average significant wave height for this location was H_s = 1.32 m. The average peak wave period was T_p = 9.27 s. The wave directions are very concentrated: 64 % of the waves come from southern direction and 36 % of the waves come from south-south-western direction. The average wave direction was 188.8°with a directional spreading of 22.8°.

The coastline has an angle of 75°relative to the north. Since the wind waves approach the coast at an angle of 23°with the cross-shore, a longshore current is induced. These longshore currents are driven by the transfer of momentum from the wave motion to the mean flow through the dissipation of energy of breaking waves. Because breaking waves only exist in the surf zone, the longshore currents are confined to that location (Bosboom and Stive, 2011). These wave-driven longshore currents are important for sediment transport and can therefore influence the location of a lagoon opening in case of a sandy coast. Because the coastline around the mouth of the Sakumo lagoon is protected by a revetment, this feature is much less important.

4.3.2. Ocean currents

The dominant ocean current is the Guinea current, flowing from west to east along the West-African coast. The current is not very strong and its intensity decreases further in onshore direction. It is not strong enough to transport sediment on its own, but because its direction is equal to the direction of the wave-induced longshore current, it can enhance wave-induced flow along the coast. (Roest, 2018)

4.3.3. Tide

The Ghanaian coast experiences a small tidal range of around 1.0 to 1.5 m. The spring tidal range in the east can be as much as 1.9 m, while in the west the tidal range is slightly smaller. As the phase of the tide is approximately equal along the Ghanaian coast, no tidal currents are induced (Roest, 2018).

4.4. Mixing and flushing

These mechanisms drive dispersion of salinity and pollutants in the water and are of importance in determining the pollutant dynamics in a lagoon.

4.4.1. Processes

Three main driving forces of mixing are wind, riverine inflow and tidal exchange. Because of the small horizontal length scales of the Sakumo lagoon, mixing by wind set-up is considered to be least important. With negligible riverine inflow in the dry season, the tidal exchange must be dominant in driving the mixing process. However, the riverine inflow is significant in the wet season and is then most likely to be the dominant mixing mechanism.

4.5. Conclusion and discussion

From the system assessment, a better understanding is gained on the hydraulics of the Sakumo lagoon. Using the values presented in this chapter, calculations on the response of the system can be made. This will be done in the following chapters.

5 Overland flow model

Since there is a lack of data on the discharges of the tributaries that flow into the lagoon, other sources of information need to be gathered. To this end, an overland flow model was set up which calculates flow and water levels that result from a predefined rainfall event. This model can also be used for assessing the flood safety of the area.

From the Hydrological Services Department (HSD), a SOBEK model was received of most of the Greater Accra region. The model was used to assess the flood risk of the Odaw basin, located 30 km west of the Sakumo lagoon.

The model is a elevation-based model calculating rainfall runoff given a certain precipitation event. It consists of a 2D digital elevation element and 1D network elements. A meteorological event precipitates directly onto the 2D grid, after which the routing of water is calculated using set roughness values.

5.1. Model setup

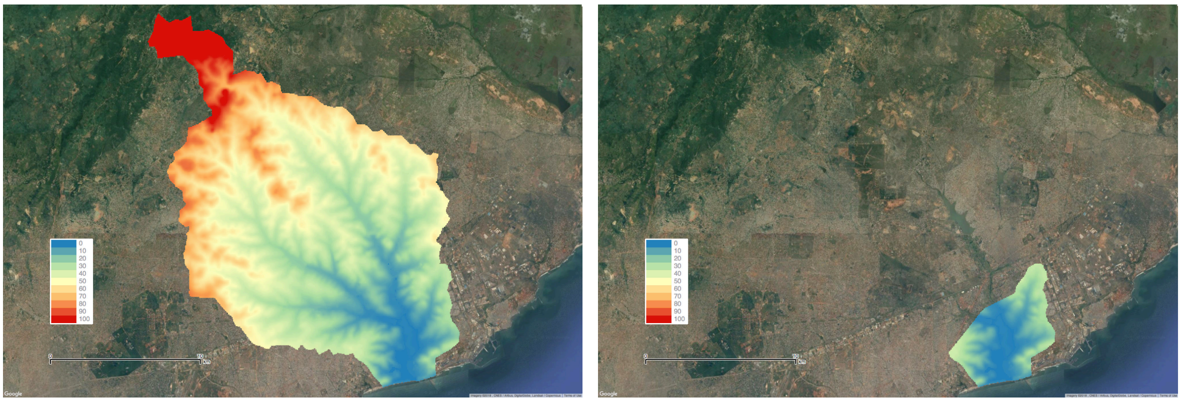
The following data is used to set up the model.

DEM A Digital Elevation Model (DEM) was received from HSD. It spans part of the Greater Accra region, which the Sakumo catchment is part of. The DEM has a resolution of 50 m and elevation values are given in centimetres. The elevation values are based on contour lines of the Lands Commission and uses National Level Datum (NLD) as reference. NLD is equal to mean sea level + 0.35 m. Information on the errors of the elevation values is unknown. QGIS was used to extract the area of the Sakumo catchment in order to reduce computing time.

Two model variants To be able to run the model for several different designs, computation time had to be decreased. Therefore, the model that spans the whole Sakumo lagoon catchment, from here on referred to as *the large model*, was run for rainfall events with various return periods. The discharge through the main tributaries leading into the main basin of the Sakumo lagoon was then extracted. These discharge time-series were used as upstream boundary conditions for a model from which a large part was cut off. This model will from here on be referred to as *the small model*. The model areas are shown in figure 5.1. While the large model ranges from 0 to 413 m + NLD, the colorbar ranges to 100 m for better visibility of height differences in the area of interest.

Decreasing the area of the model was done under the condition that the boundary conditions should be placed sufficiently far away from the lagoon mouth that changes to the mouth do not affect the upstream discharges. This assumption was validated and resulted in a difference of less than 1% for radically different mouth designs, which was deemed a small enough difference to provide accurate results for the small model. The locations of these boundary conditions are shown in figure 5.2.

Connection with the sea In the DEM, the connection of the lagoon with the sea is represented by an open connection with a length of two grid cells (100 m). In reality, this is not the case. Water is severely hindered from flowing out in to the sea due to the fact that only a small culvert is connecting the sea with the lagoon. The DEM was altered to create a closed dike-like structure, with a width of one grid cell,



(a) Large model (highest point is 413 m + NLD) (b) Small model

Figure 5.1: The two model areas used for the computations

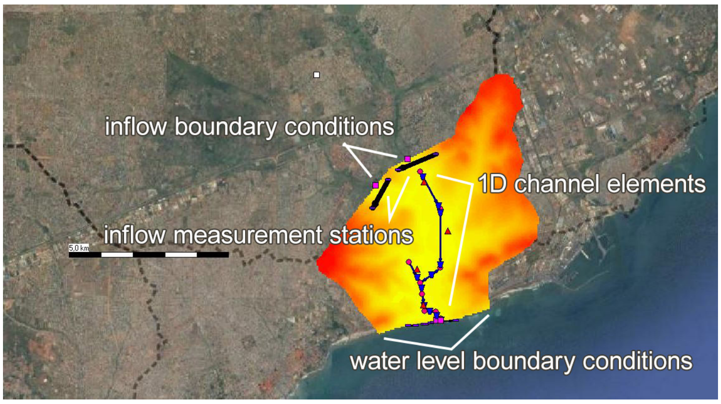


Figure 5.2: Location of measurement lines in the large model and boundary conditions used for the small model

between the lagoon and the sea. The height of the dike was estimated at 4.6 m + NLD (observation on site, 2 March 2018). The culvert and storm drain connecting the lagoon with the sea were measured using a gauge staff and measuring tape. They were added to the model as 1D elements, shown in figure 5.3. The bottom level of the culvert and storm drain were estimated at -0.66 m + NLD and 1.30 m + NLD respectively. They are represented in the model as one rectangular structure with a cross-sectional area equal to the cross-sectional area of the two pipes. The same was done for the four storm drain pipes.

Meteorological data Precipitation data were retrieved for the Tema measuring station, located a few kilometres from the Sakumo lagoon. The data consists of daily precipitation rates from 1961 to 2017. The IDF curve for this location was also retrieved.

To develop a representative hydrological scenario, a hydrological model was used to design an effective precipitation event from the IDF curves. Effective precipitation is what is left when all losses are accounted for. These losses are evaporation, infiltration and local storage. They are included in the calculation as a set of correction factors on the rainfall time series that is used as input to the hydraulic model. See appendix D for more details about the calculation.

Tidal data The sea side boundary was modelled as a water level boundary. Water level time series have been extracted from the University of Hawaii Sea level Center (University of Hawaii Sea Level Center, 2016). The water levels were taken from the closest measuring station at Takoradi (200 km west of the Sakumo lagoon). Since the tidal range does not vary much along the Ghanaian coast, this time-series was deemed representative for the coast of the Sakumo lagoon.

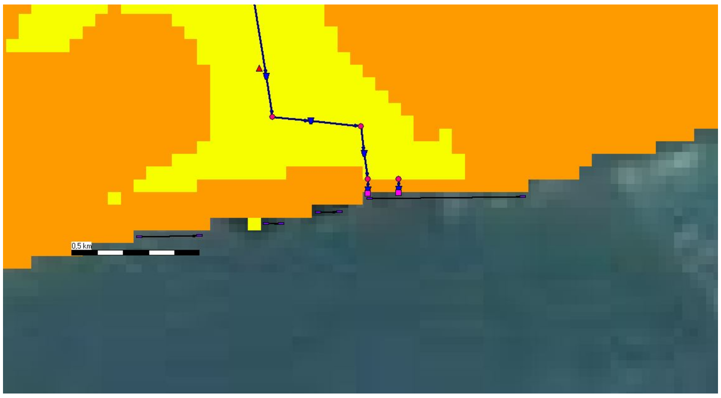


Figure 5.3: 1D elements and water level boundaries at the mouth of the Sakumo Lagoon

Hydraulic roughness Land cover data was combined with a standard land cover manning table to estimate the rainfall runoff roughness. The Manning roughness was specified on each grid cell of the DEM.

Upstream structures Heights of the upstream dams have up until now not been found. The elevation values originally given in the DEM file were therefore not altered.

Computational grid The model was run using a rectilinear grid with 50x50 m grid cells. A time step of one hour was used with various simulation periods.

5.2. Validation

Since very little data is available on discharges and water levels, the validation and calibration has proven to be difficult. The model is validated using water levels and discharges through the culvert.

5.2.1. Steady state validation

Pauly (1975) measured the discharge through the culvert for a cycle of 24 hours in 1971. This is not sufficiently recent for an accurate validation, but since this is the only discharge data available it will nevertheless be used to validate the model.

The large model is run for a once in 5 year rainfall event, the simulation time being 25 hours. During this run, the discharge entering the Sakumo basin is computed. This discharge is used as the boundary condition for the small model, which is subsequently run for a period of 20 days. After the initial rainfall event, no rain precipitates on the area. In this way, a steady state is reached where only the tide-induced flow through the culvert still varying in time. The discharge through the culvert can then be compared to the discharge measured by Pauly (1975).

Figure 5.4 shows the computed discharge through the culvert for the small model for the 20-day simulation period.

In the final days of the computation, the initial rainfall event has little effect on the flow through the culvert. Furthermore, the tidal boundary condition was made to correspond to the one reported by Pauly (1975). Hence, for the final days of this computation the computed discharges can be compared to the discharges reported by Pauly (1975). The values obtained from the model have been mirrored in the x-axis in order to facilitate comparison with the measurements. The comparison can be seen in figure 5.5.

It can be seen that the results match quite well. Measured inflow into the lagoon is around 3.0 m^3/s for both the simulation and the measurements, while during outflow the discharge is around 1.0 m^3/s. The skewness is also represented well in the model, meaning that the inflow of water occurs during a shorter time period than the outflow of water.

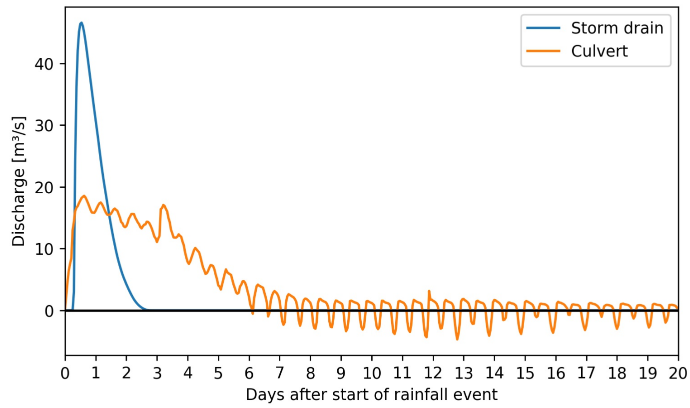
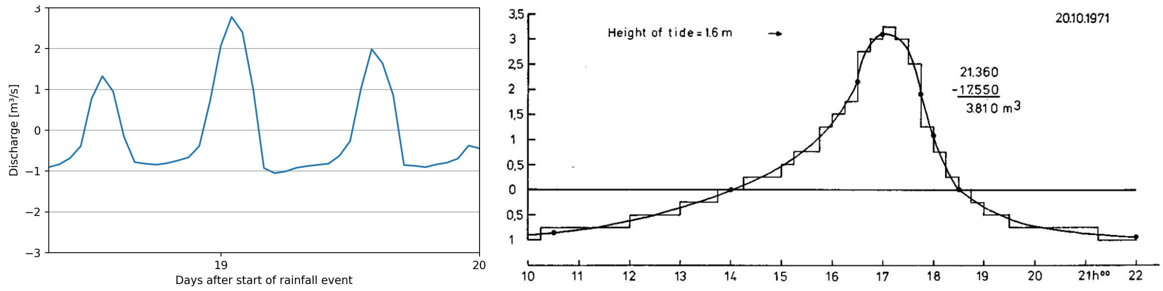


Figure 5.4: Computed discharge through culvert and storm drain after rainfall event T = 5



(a) Computed discharge

(b) Discharge measured by Pauly (1975)

Figure 5.5: Comparison of computed and measured discharges through the culvert in steady state

5.2.2. Flood validation

No historical flood maps or water levels have been found for the Sakumo lagoon. Instead of using measured data, the model is validated as to its predictive use for flooding using water levels reported by locals and a news article.

The model will be validated with data of the flood of 1997. Reportedly, during this flood the Accra-Tema road was inundated (Local fishermen, pers. comm.). Furthermore, a church called the 'Deeper Life Bible Church' in the vicinity of the main basin was submerged with only its roof above water (GhanaWeb, 1997). These two references will be used to validate the model. From the news article, it was determined that the flood took place on or few days before 19 June 1997.

The rainfall events leading up to the flood can be seen in figure 5.6. In the days prior to 19 June, the publication date of the news article, heavy rains have been recorded.

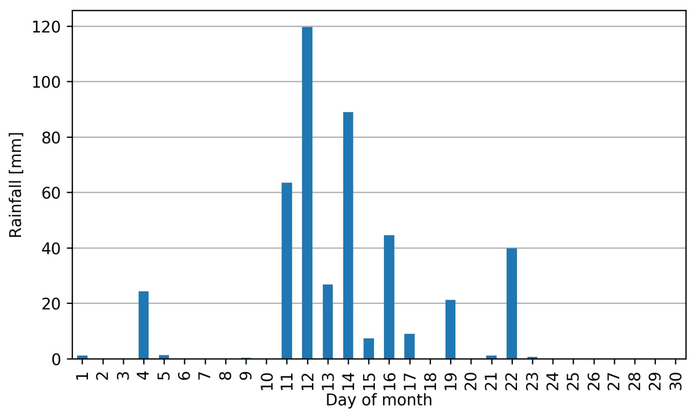


Figure 5.6: Daily rainfall during the month of the 1997 floods

The recorded rainfall in the period of 11 to 17 June 1997 has been transformed to 24-hour rainfall events using the method described in section 5.1 and appendix D. The resulting hourly rainfall was then used as input for the large model. The storm drain was not included in the model since it was built after this flood occurred.

Firstly, the water level at the culvert will be assessed. According to fishermen, the Accra-Tema road was inundated during this event. Figure 5.7 shows the local water depth at the culvert for the entire 7 day period. The figure shows that four days into the rainfall event, on 14 June 1997, the road and dike are indeed flooded due to insufficient discharge capacity of the culvert.

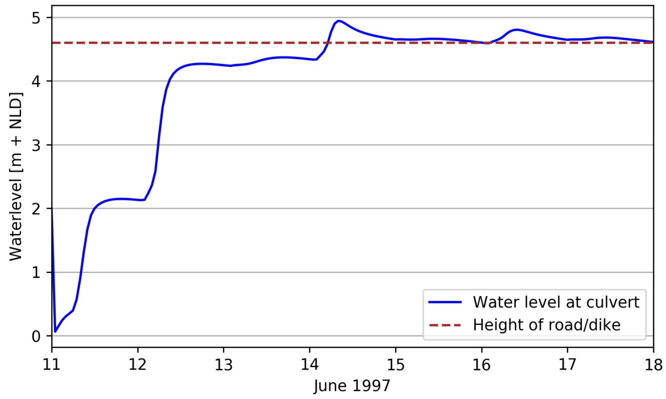


Figure 5.7: Computed water levels near mouth as a result of the June 1997 rainfall events

Secondly, the water levels near the aforementioned church are validated. This church is located somewhere in an area called ‘community five extension’ in Tema. Its exact location and height remains unknown. Figure 5.8 shows the water depth in the vicinity of the church during the flood event.

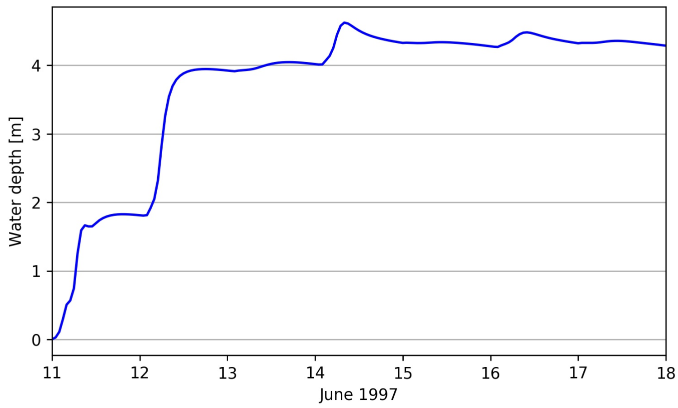


Figure 5.8: Water depth near the church during the 1997 flood

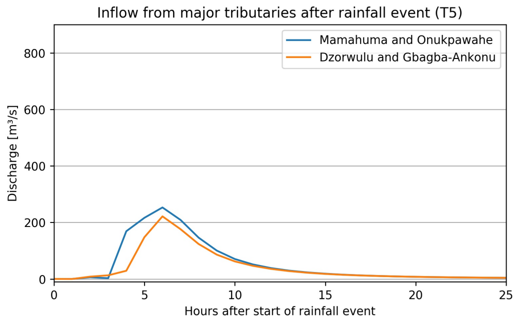
It can be seen that the water depth reaches values of 4 to 4.5 m. Assuming that the church has a height of a two storey building, it is indeed possible that only the roof was visible during the floods.

5.3. Results

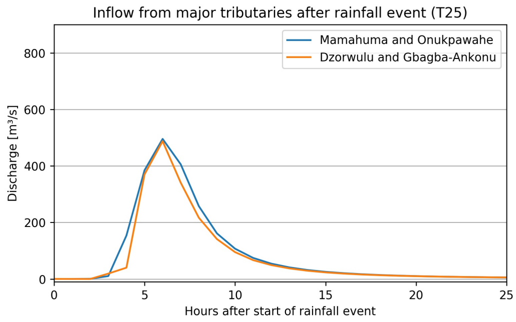
After validating the model, the model is used to calculate the discharges from upstream into the Sakumo lagoon for various rainfall events.

The model has been run using a rainfall event with a return period of 5, 25, 50 and 100 years. The large model was run with a simulation period of 25 hours. Measuring stations were added in the two largest tributaries, namely the Mamahuma/Onukpawahe and Dzorwulu/Gbagba-Ankonu. The discharge into the basin through these tributaries is shown in figure 5.9.

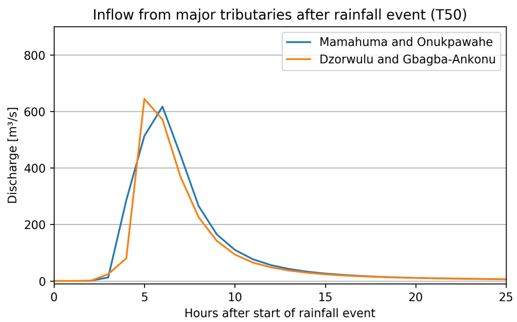
The inflow to the basin for a once in 5 year event is significant. The inflow from the Mamahuma-Onukpawahe stream equals 5.08×10^6 m^3 and the inflow from the Dzorwulu-Gbagba-Ankonu stream equals 3.93×10^6 m^3 making the total inflow 9.01×10^6 m^3 in a 24-hour period. The initial estimate of the



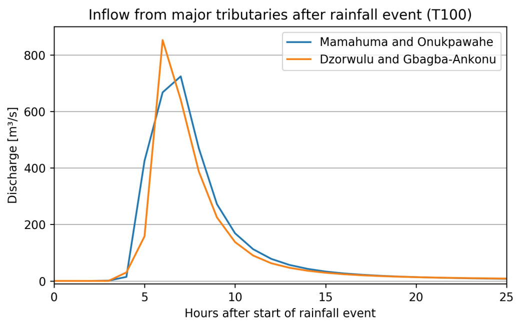
(a) T = 5 years



(b) T = 25 years



(c) T = 50 years



(d) T = 100 years

Figure 5.9: Inflow into lagoon from main tributaries after various rainfall events

inflow resulting from a once in 5 year rainfall event was 11.8×10^6 m^3 in a 24-hour period, as calculated in section 4.2.5. The order of magnitude is thus comparable, yet the amount was overestimated by about 30 %.

5.4. Conclusion

The overland flow model was used to gain insight into the flood safety of the surroundings of the lagoon after rainfall events with various return periods. Because of the limited options for validation of the model, the results should be interpreted with caution. Nevertheless, its results can be used because the aim of this study is to compare several mouth designs of the Sakumo lagoon. The model will be able to provide insight into the relative flood safety of various design situations. However, in order to make accurate predictions for the flood safety, the model will need to be calibrated and validated using more recent and more accurate data.

Furthermore, the model was used to make estimates for the inflow into the lagoon resulting from rainfall runoff. While the same problem of the limited validation options persists, these estimates are deemed more accurate than the simple hand calculations made in section 4.2.5. This is because this model has been used and calibrated for the Odaw basin, which is a basin nearby and in a very similar climate. Therefore, these results can be used to make predictions for mixing, flushing and sediment transport in the lagoon.

5.5. Discussion

Steady state validation This method used for the steady state validation in section 5.2.1 is disputable. Measurements from Pauly (1975) have been done in 1971, more than 45 years ago. The lagoon was in a very different state back then than it is now. It is currently overgrown with plants and suffers from heavy siltation. Furthermore, the storm drain was not present and the upstream tributaries were not channelised in 1971. During the steady state exchange of water between the lagoon and the sea, the storm drain is above the water level at all times. Therefore, the presence of the storm drain in the model will not affect the results. However, the historically different shape of the lagoon can pose problems. The in- and outflow rates may differ due to changes in lagoon morphology. In order to properly validate the model, discharge measurements in the culvert have to be performed.

Flood validation The validation of the model with the methods used in section 5.2.2 is again disputable.

Regarding the validation using the flooding of the road, many estimates are used. Knowing that water levels exceeded the height of the Accra-Tema road during the 1997 flood could be a good way to validate the model. However, the depth of the water flooding the road remains unknown. Furthermore, the height of the embankment was estimated from personal observation on site, which introduces an additional error.

For the flooding of the church, the validation was again based on crude estimates. The exact location of the church remains unknown, as well as its height. These are estimated to the best of our ability, yet this does not provide for accurate model validation. In order to properly assess the errors of the water levels computed in the model, the location and height of the church need to be traced. However, even when these are quantified, the validation is still based on a single remark of an interviewee in a news article.

In order to properly validate the model for its use for flood risk assessment, water depths should be monitored in the Sakumo lagoon over long time periods.

6 Mixing model

Little is known about mixing, salt intrusion and pollutant dynamics in coastal lagoons. However, much more is known about salt intrusion in estuaries. Because pollutants obey the same transport equations as salt, the Sakumo lagoon is simplified to an estuary with exponentially varying width. Because of this simplification, results provided in this section have questionable validity. Nevertheless, they can prove useful when compared to alternative design situations discussed in chapter 9.

Figure 6.1: Simplification of the Sakumo lagoon to an estuary with exponentially varying width

The geometry of the simplified basin is shown in figure 6.1. It has a depth of 0.55 m and an exponentially varying width. The shape factor was fitted to a satellite image. The width of the basin varies exponentially and is given by the following equation:

$$B(x) = B_0 \exp\left(-\frac{x}{b}\right); \tag{6.1}$$

with x the distance from the mouth and:

width at mouth	B_0	=	300 m
shape factor	b	=	600

6.1. Dimensionless numbers

A simple dimensionless number for determining the relative dominance of the riverine and tidal inflow is the Canter-Cremers number (Savenije, 2012), defined as the ratio of fresh water volume entering the water body during a tidal cycle ($Q_f T$) to the tidal prism, P_t. A high Canter-Cremers N means that the influence of the riverine inflow is relatively high. N is therefore expected to be high in wet season conditions and low in dry season conditions. The Canter-Cremers number is given in equation 6.2.

$$N = \frac{Q_f T}{P_t} \tag{6.2}$$

The tidal period T is 44000 s (12:25 hours). For Q_f, both the average wet- and dry season inflow are used. These are 0.341 m^3/s and 0.074 m^3/s, respectively, as determined in section 4.2.5.

The flood volume is estimated using the method proposed by Savenije (2012). It is calculated by multiplying the cross-sectional area at the mouth of the lagoon A_0 with the tidal excursion at the mouth E_0.

$$P_t \approx A_0 E_0 \tag{6.3}$$

For A_0, the cross-sectional area of the mouth of the simplified estuary at mean water level is used. With a width of 300 m and a water depth of 0.55 m, this results in $A = 165$ m^2.

The tidal excursion is the distance which a water particle travels between low water slack and high water slack. It is therefore also the length scale of the longitudinal tidal mixing process. It is calculated using the formulation provided by Savenije (1993):

$$E_0 = 1.08 v_0 \frac{T}{\pi} \tag{6.4}$$

where v_0 is the tidal velocity amplitude at the mouth and T is the tidal period. v_0 is estimated by taking the maximum and minimum discharge through the lagoon mouth at spring tide and subsequently dividing these by the cross-sectional area of the proposed simplified estuary. Initially, these values were estimated from measurements taken by Pauly (1975). However, the values presented here are drawn from the model results that will be explained in section 5 because they will be compared to values calculated for various design alternatives in chapter 9.

When $v_0 = 1.3$ m/s, the tidal excursion E_0 = 155.3 m. This leads to a tidal prism P_t = 26×10^3 m^3. For the dry season, the Canter-Cremers number N then becomes 0.13, indicating that the influence of riverine inflow is far smaller compared to the wet season, in which the Canter-Cremers number N is 0.59.

For determining the relative importance of gravitational circulation due to riverine inflow compared to tidal forcing to the mixing process , the Estuarine Richardson number N_R (Fisher, 1972) is calculated in equation 6.6. This dimensionless number is the product of the densimetric Froude number, given in equation 6.5, and the Canter-Cremers number, given in equation 6.2.

$$F_d = \frac{\Delta\rho}{\rho}\frac{gh}{v^2} \tag{6.5}$$

where $\Delta\rho/\rho$ is the relative density, which is assumed to be 25/1000. h is 0.55 m, the depth of the basin, and $v = v_0$.

The Estuarine Richardson number is then calculated using the following equation:

$$N_R = F_d N \tag{6.6}$$

If N_R is high, the riverine inflow provides enough energy to maintain a sharp interface and subsequently stratification usually occurs; if it is low, there is enough energy available in the tidal currents to mix the water body well and there is no stratification (Savenije, 2012). Because of the small vertical dimensions of the Sakumo lagoon, little stratification and therefore a low Estuarine Richardson number are expected.

Using the values explained above, N_R is 0.73 in dry season conditions, while in the wet season N_R is 5.92. The high wet season value indicates the large amount of potential energy provided by the riverine inflow. In the dry season, the potential energy provided by the tide is far more important for the mixing process.

6.2. Salt intrusion length

The intrusion length at High Water Slack (HWS) in an estuary with an exponentially varying cross-section can be calculated using equation 6.7:

$$L^{HWS} = a\ln(\frac{1}{\beta} + 1) \tag{6.7}$$

where:

$$\beta = \frac{KaQ_f}{D_0 A_0} \tag{6.8}$$

where β is the dispersion reduction rate, determining the longitudinal variation of D. K is Van der Burgh's coefficient and D_0 is the dispersion coefficient at the mouth.

In order to predict the salt intrusion length in the lagoon, estimates on the dispersion coefficient and Van der Burgh's coefficient are necessary. These coefficients will be estimated using the method proposed by Savenije (2012).

A predictive expression for the dispersion coefficient at HWS is obtained by Savenije (1993):

$$\frac{D_0^{HWS}}{v_0 E_0} = 220\sqrt{40}\frac{h}{a}N_R^{0.5} \tag{6.9}$$

In equation 6.9, the left hand side is the inverse of the Péclet number, being the ratio of the advection to the dispersion of a transport process.

Savenije (2012) provides an empirical fit relation for predicting a value for Van der Burgh's coefficient, K. However, this equation should be used with caution and should only be used as a first estimate of K.

$$K = 0.3 \times 10^{-3}\left(\frac{E}{H}\right)^{0.65}\left(\frac{E}{C^2}\right)^{0.39}(1-\delta b)^{-2.0}\left(\frac{b}{a}\right)^{0.58}\left(\frac{E_a}{A_0'}\right)^{0.14} \tag{6.10}$$

In this formulation, several terms can be neglected. Because of the small dimensions of the lagoon, $(1-\delta b)$, which accounts for tidal amplification or damping, is assumed to be 1. b/a accounts for bottom slope which is assumed to be negligible in the basin. E_a/A_0' needs to only be used in case there is a second branch that needs to be accounted for. This leaves us with:

$$K = 0.3 \times 10^{-3}\left(\frac{E}{H}\right)^{0.65}\left(\frac{E}{C^2}\right)^{0.39} \tag{6.11}$$

in which E/H is the ratio between the tidal excursion and the spring-tidal range, a key tidal parameter that is related to the geometry of the estuary. Furthermore, E/C^2 is a channel roughness indicator.

6.3. Time scales

The first time scale that will be assessed is the time scale of the riverine flushing, T_f. It corresponds to the particle travel time through the estuary.

$$T_f = A_0\frac{a}{Q_f}\left(1 - \exp\left(-\frac{L}{a}\right)\right) \tag{6.12}$$

In the wet season when the riverine inflow is the dominant flushing mode, T_f = 4.9 days, while in the dry season it T_f is 15.5 days.

The second time scale, T_t, is a measure for the flushing of the estuary through tidal pumping. It is the ratio between the basin volume V and the tidal prism P_t. Because the tidal prism is defined per tidal cycle, it has to be divided by the tidal period:

$$T_t = VTP_t \tag{6.13}$$

In the wet season, T_t = 90 days. In the dry season, it is 30 days. This time scale does not take into account diffusion and intrusion length, which are important for the tidal flushing process. Because of its simplicity it is used to estimate the relative time scales of the flushing for the various alternative designs in chapter 9.

The results of the calculations in this section are summarized for convenience in table 6.1 and 6.2.

Table 6.1: Values of parameters and coefficients

	A_0	v_0	E_0	P_t	N	N_R	D_0	K
Dry season	1.29	1.30	155.31	25.6×10^3	0.13	0.73	1.73	2.95×10^{-3}
Wet season	1.29	1.30	106.78	25.6×10^3	0.59	5.29	3.37	2.0×10^{-3}

In which:

A_0 = cross-sectional area of the mouth [m^2]
v_0 = flow velocity at the mouth [m/s]
E_0 = tidal excursion [m]
P_t = tidal prism [m^3]
N = Canter-Cremers number [-]
N_R = Estuarine Richardson number [-]
D_0 = diffusion coefficient [-]
K = Van der Burgh's coefficient [-]

Table 6.2: Values of calculated parameters

	L^{HWS} [km]	T_P [days]	N_P [-]	N_Q [-]	N_D [-]
Dry season	4.61	30	-74×10^3	0.10	8.7×10^{-3}
Wet season	4.55	90	17×10^3	0.31	17.3×10^{-3}

In which:

L^{HWS} = salt intrusion length at high water slack
T_P = flushing time due to the tidal prism
N_P = overall importance of rainfall for the rate of change of salinity
N_Q = importance of fresh water inflow for the rate of change of salinity
N_D = overall impact of dispersion related to tidal forcing for the rate of change of salinity

6.4. Conclusion and discussion

It has been determined which processes dominate mixing and flushing. The lagoon is schematised as an estuary with exponentially varying width, but this schematisation was not validated. Therefore, the values calculated using this schematisation are of questionable validity. However, it is assumed that they can be very useful in judging the change in dominance of the various processes in case of different design situations. They will therefore be used for comparison to the various design situations that will be presented in chapter 9. This can be valuable for rating the designs on their effectiveness for improving the quality of the lagoon.

Validating this model should be done by measuring the spatial variation of the salinity in the basin at high water slack. The results can then be compared to the salt intrusion parameters calculated in this chapter. The model should then be calibrated to yield accurate results.

7

Water quality and pollution

Several stakeholders have expressed their concerns about the deteriorating water quality in the Sakumo lagoon. The current level of pollution of the lagoon was investigated as well as the historical trends. This is done in order to predict the future state of the lagoon, and to see whether an intervention is needed. In order to assess the water quality, water samples have been taken and analysed and an estimation of the trophic state of the lagoon is made.

7.1. Current situation

An investigation into the current situation of the lagoon is performed to make an estimation of the rate of deterioration. The results of the current situation have to be compared with historical data. The current situation is analysed on the following parameters: ammonia-nitrogen (NH3-N), nitratre-nitrogen (NO3-N), ortho-phosphate (PO4), pH-value, dissolved oxygen (DO), temperature and conductivity. These parameters are chosen for the reason that these parameters can tell something about the trophic state of the lagoon and the pollution by domestic waste water and agricultural waste water. Also an advantage of these parameters is the availability of historical data of these parameters in the lagoon.

7.1.1. Materials and methods

Field work was done on 2 February 2018. This date was chosen because it was spring tide and maximum in- and outflows could be observed. Samples were taken at various locations. Three locations were sampled near the lagoon mouth, during both low water (10:08) and high water (16:30). Two more locations were sampled during high water. The first of these locations is a small pond separated from the main water body located near the lagoon mouth, the second location at the sea side of the embankment. The measurement locations are shown in figure 7.1.

The tidal range was 1.6 m, and the resulting difference between the high and low water levels at the measurement locations near the lagoon mouth was about 40 cm. During high tide, water was flowing from the sea into the lagoon while during low tide the water was flowing in opposite direction. For this reason, the three measurement locations near the mouth contained differently sourced water at the two measurement times. At these locations, measurements taken during low tide will be referred to as samples containing lagoon water, while the measurements taken during high tide will be referred to as samples containing sea water from this point.

The parameters temperature, dissolved oxygen, pH and conductivity were measured in situ. For the nutrient analysis, samples of 500 ml were taken and immediately stored in an ice cooled box. The bottles were then frozen and the samples were analysed three days later. The concentrations of ammonia, nitrate and phosphate were analysed using Hach reagent powder pillow tests. After the reaction with the reagent, the nutrient levels were measured by a spectrophotometer. The four samples containing lagoon water had to be diluted for the ammonia and phosphate tests. For analysing ammonia, the sample was diluted to a ratio of 1:50 and for analysing phosphate the sample was diluted to a ratio of 1:10.

Figure 7.1: Measurement locations at the mouth of the Sakumo lagoon

7.1.2. Results

The results of the measurements and sampling analysis will be presented in this section. The values measured in-situ are presented in table 7.1, while the results of the analysis of nutrient concentrations are given in table 7.2.

Table 7.1: In-situ water quality measurements by location

		Lagoon water			Sea water			Pond
Temperature	°C	28.91	±	0.64	29.48	±	0.14	33.03
pH	-	6.09	±	0.29	8.14	±	0.06	7.68
Dissolved Oxygen	mg/l	0.38	±	0.04	6.16	±	0.09	6.51
Oxygen saturation	%	5	±	0.61	99	±	4.98	94
Conductivity	mS/cm	2.78	±	0.45	53.43	±	2.02	15.10
Salinity	ppt	1.47	±	0.25	35.07	±	1.79	8.60
Density	kg/m^3	1000	±	0.00	1022.13	±	1.33	1001.30

Table 7.2: Nutrient concentrations in mg/l by location

		Lagoon water			Sea water			Pond
Phosphorous	PO4	7.43	±	0.25	0.08	±	0.03	1.30
Ammonia	NH3-N	26.82	±	5.70	0.07	±	0.03	1.72
Nitrate	NO3-N	2.37	±	0.21	0.60	±	0.26	2.00

7.2. Trends

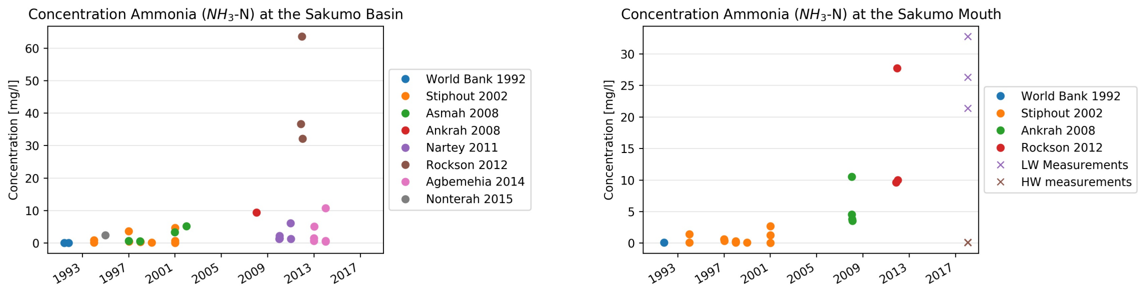
A large number of studies has been done on the water quality of the Sakumo lagoon. Unfortunately, these studies are not completely suitable for comparison, since the measurement locations, times and equipment may differ greatly. Especially the tidal influence can greatly affect the measurements. The intrusion of sea water can cause great differences between the measurements taken during high and low tide.

Nevertheless, a trend analysis has been done on these recorded measurements. For these trend analyses, studies were selected that corresponded to one another in terms of measurement locations. The results of these analyses will be presented in this section. In addition to the trend analyses, an explanation of the values of the parameters is given for every parameter.

7.2.1. Ammonia (NH3-N)

The ammonia concentrations in the lagoon are extremely high. According to Henze et al. (2001), the average concentration of NH3-N is 30 mg/l in moderate municipal wastewaters. The mean concentration of ammonia in the lagoon water was measured at 26.8 mg/l, with a maximum of 32.8 mg/l.

The extremely high levels of NH3-N and relative low levels of NO3-N and DO indicate that there is a lot of organic waste in the water, as ammonia is a nutrient present in faeces. Ammonia is transferred into nitrite and nitrate when enough oxygen is present.



(a) Basin

(b) Mouth

Figure 7.2: Ammonia values in literature

The values found in literature for ammonia concentrations in the Sakumo lagoon are shown in figure 7.2. In figure 7.2b, our measurements are added.

The concentrations of ammonia found in our measurements are in line with the increasing trend of the last decade. This suggests that the amount of organic pollutants such as faeces and fertilizers entering the lagoon is increasing.

7.2.2. Nitrate (NO3-N)

Compared to the ammonia concentrations, the measured nitrate concentrations are surprisingly low. It is likely that this is related to the fact that oxygen is needed to transfer ammonia into nitrate. Combined with the low DO concentrations, this indicates that there is an oxygen deficiency. Nitrate concentrations are expected to be higher when more oxygen is present in the lagoon.

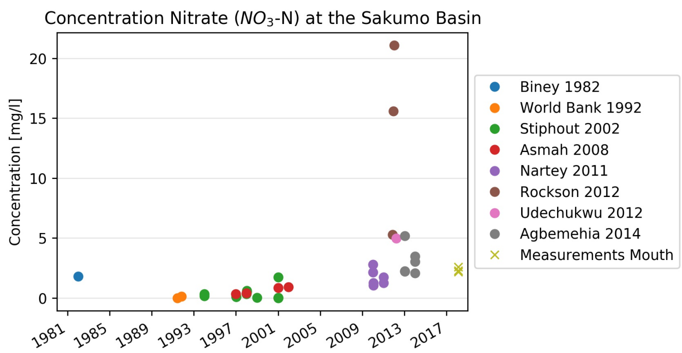
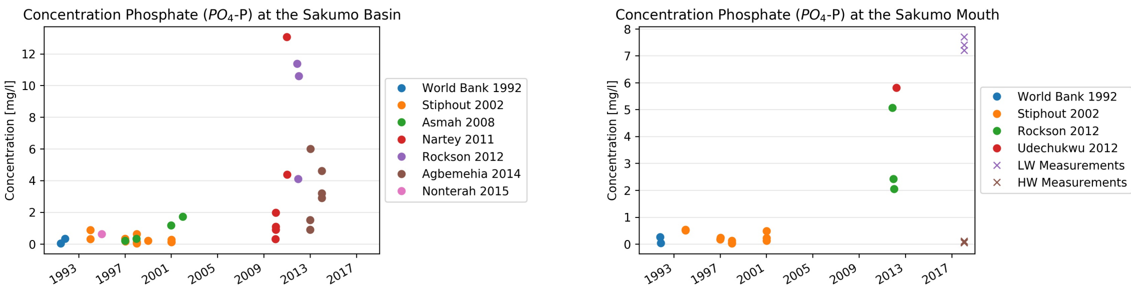


Figure 7.3: Nitrate values in literature

The nitrate concentrations found in literature are shown in figure 7.3. The values measured by us are also included in the figure. As a result of the increase of ammonia concentration, explained in the previous section, the nitrate concentration is rising as well. However, the nitrate concentration rises at a slower rate.

7.2.3. Phosphate (PO4)

Phosphate is often the limiting factor in algal growth. That is clearly not the case in this lagoon as phosphate concentrations are high. These concentrations again suggest that the lagoon is polluted with organic pollutants such as faeces and fertilizers.



(a) Basin (b) Mouth

Figure 7.4: Phosphate values in literature

PO4 measurements in the basin as well as at the lagoon mouth were taken into account in the analysis. An increasing trend is visible in the PO4 concentrations, shown in figure 7.4. Our results are in line with this increasing trend. The increase in phosphate and ammonia concentrations confirms that the water quality in the lagoon is deteriorating.

7.2.4. Acidity (pH)

Studies were selected in which measurements were taken in the main basin. Only these measurements were used in this analysis. If multiple locations in the main basin were measured, the average pH of these locations was calculated and used for the analysis. The results are shown in figure 7.5. Both Asmah et al. (2008) and Agbemehia (2014) report higher pH values in the dry season than in the wet season. In 1997 to 2002, these differences were reportedly minimal, while in 2013-2014 they were significant.

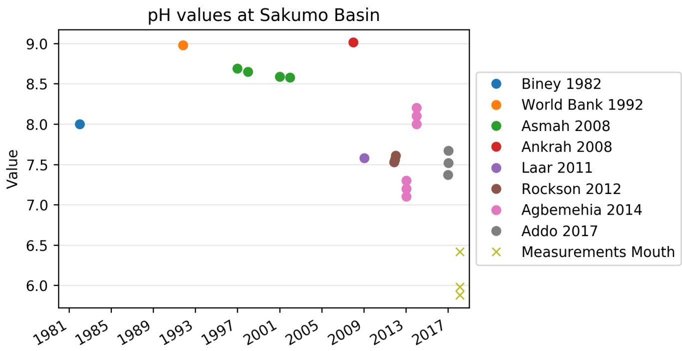


Figure 7.5: pH values in literature

When looking into historical literature, the measured pH in the main basin of the Sakumo lagoon seems to gradually decrease. The lagoon water is becoming increasingly acidic, which has been shown to have adverse effects on the lagoon biology (Raddum and Fjellheim, 1984). Fluctuations in pH-value are possibly the result of photosynthesis by algae (Asmah et al., 2008).

The values obtained during low tide are quite acidic for fresh surface water. The the guideline value by the Environmental Protection Agency of Ghana is 6 to 8. According to Hamill and Bell (2013), the pH of of most natural waters ranges from 6.0 to 8.5. The measured mean value is on the low side, yet within this range. It should be noted that at one location, a pH of 5.88 was measured.

Taking into account the adverse effects of acidity of surface water and the notion that the pH in the dry season is generally higher than in the wet season, this parameter should be carefully monitored.

7.2.5. Dissolved oxygen

The dissolved oxygen (DO) concentration of the lagoon water was measured at 0.38 $\pm$ 0.04 mg/l, which corresponds to an oxygen saturation of 5%. The sea water had DO concentrations of 6.16 $\pm$ 0.09 mg/l, corresponding to oxygen saturations around 98%. The DO concentration in the pond next to the lagoon mouth was 6.51 mg/l in the afternoon. With a water temperature of 33.03 °C, this concentration leads to an oxygen saturation of 94%.

The DO concentration in the sea water is considered normal. However, in the lagoon water it is very low. This is attributed to the high biological and chemical oxygen demand of the water flowing out of the lagoon. The measured oxygen saturation in the pond was higher than expected. Because of the high temperature of the water, which negatively influences the solubility of oxygen, and the polluted state of the lagoon, a low DO concentration was expected. The relatively high oxygen saturation in the pond is presumably due to the activity of algae.

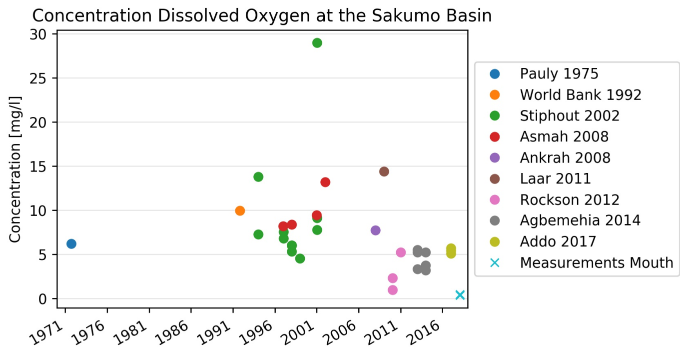


Figure 7.6: Dissolved Oxygen values in literature

A great variance of DO concentrations follows from the historic data , with a slightly decreasing trend. The concentrations found in our measurements are far lower than literature suggests. This deviation is a result of the increase in ammonia and possibly of the decay of plants and organic matter in the lagoon. From Asmah et al. (2008) one learns that before 2008 the dissolved oxygen concentrations all exceeded 6.0 mg/l. This means that the DO has decreased rapidly over the last ten years. As the minimum DO concentration necessary for the optimum growth and development of fish is 5.0 mg/l (Gray et al., 1975), the fact that all our measurements are less than this value is cause for great concern.

7.2.6. Temperature

The temperature difference between the measurement locations was minimal. The water temperatures varied from 28.19 °C to 29.64 °C over the course of the day. The only location with a significantly higher temperature was the water in the small pond next to the mouth . Here, a temperature of 33.03 °C was measured. The temperature of the water is important for the solubility of oxygen in water. In water with higher temperatures the concentration of dissolved oxygen will be lower.

7.2.7. Salinity

The conductivity, and thus salinity, of seawater is much higher than the conductivity of fresh water. This difference is clearly seen in the high- and low water measurements. Therefore, it is confirmed that the water flowing into the lagoon at high water was almost purely sea water.

Conductivity measurements are not recorded sufficient enough to say something about trends in the literature found. The location and time in a tidal cycle is important to compare data on conductivity. The most valuable information obtained from the conductivity measurements is the proof of analysing seawater during high tide.

7.3. Trophic state of the lagoon

The trophic state index (TSI) is estimated to obtain information on the grow rate of algae and plants in the lagoon. With high TSI values, algae blooms are likely to occur.

Based on the phosphorus concentrations and the equation for a trophic state index found by Carlson (1977):

$$TSI(TP) = 10(6 - \frac{ln(\frac{48}{TP})}{ln(2)}) \tag{7.1}$$

a trophic state index of 116.6 is found. The value of the TSI represents the amount of the algal biomass. With every step of 10 within the TSI range, the algal biomass doubles. The lagoon can for this TSI number be classified as an eutrophic lagoon.

The low DO concentrations found in the lagoon water might be caused by the decay of dead plants and algae, and transformation of ammonia to nitrite and nitrate. This is different from what one would expect from classical eutrophic waters, where DO concentrations during the day are relative high due to photosynthesis. At night the DO drops because of the absence of light. During the day a low concentration is measured, but more measurements are needed to proof the algal activity and behaviour of it.

7.4. Temporal differences

In time, the quality of the water in the lagoon mouth differs a lot, due to the composition of the water from seawater and the effluent city drains and drainage channels. The effect of the tidal inflow in the main basin is not researched yet, as it is not clear of some researches when in the tidal cycle measurements were taken. To measure this difference, the water quality should be measured every time at the same water height of the tidal cycle, preferably around the same time during the day.

Besides a big difference in water quality parameters between high and low water, there is also a difference in water quality in the course of the year. The variation in concentrations over the year is significant, as determined from monthly measurements by Nixon et al. (2007). In 2001, the concentration of ammonia ranged from almost 0 mg/l to a level of 7.32 mg/l. However, a clear trend was not found in that report, thus it is not certain what causes the fluctuations during a year. For this problem more measurements over a longer period are needed. For example monthly or, even better, weekly measurements over more than one year of sampling.

7.5. Possible causes

There are a few possible causes which are likely to be the cause of the water quality deterioration in the lagoon. The main problem is the quality of the water flowing into the lagoon. This water comes from communities, industries and an irrigation scheme.

7.5.1. Communities

The communities adjacent to the lagoon have a total population of 103.123 people in 2010. In the same year only 39,5 % of the households in Tema were discharging domestic waste waters into the sewage system (Ghana Statistical Service, 2014). For this reason, it is likely that the largest part of the domestic waste water of these communities ends up in the lagoon. Furthermore, the bulk of the waste water ending up in the sewage system is unlikely to have been treated, since only 8% of waste water in Ghana is being treated (Ghana Statistical Service, 2014). The problem of domestic waste water discharge into the lagoon is likely to intensify, because of the increase in industry and population in the area.

7.5.2. Industry

The main industrial site in Tema, the free zone area, is east of the Tema harbour and thus not adjacent to the lagoon. It is unlikely that this industrial site discharges water into the lagoon. Nevertheless, there are factories upstream of the lagoon that discharge their water into the Sakumo basin, for example the Coca-Cola Bottling Company (Agbemehia, 2014). The effluents are not as severe as the effluent from the heavy industry in the east, but do cause pollution in the lagoon. The reason for this is that some companies have a treatment plant, before discharging water into storm drains (van Stiphout, 2002).

7.5.3. Irrigation

The upstream irrigation dams may also have a negative effect on the lagoon. The amount of water entering the lagoon is decreasing as a result of intensifying agriculture. This means that concentrations of nutrients in the lagoon will be higher. Additionally, the intensifying agriculture also implies more use of fertilisers. The use of fertilisers by the farmers in the irrigation scheme loads the water with nutrients, which end up in the lagoon (Abatemi-Usman et al., 2010).

The water in the artificial lakes is not only used for irrigation, but also for washing and as a domestic waste water dump site of the people living close to the water.

7.6. Conclusion

The water quality of the Sakumo lagoon is getting worse. The water of the lagoon shows more similarities with raw sewage water, than with the water quality of a natural site. It is unknown which sources contribute most to the pollution in the lagoon. It is likely that it is a combination of the industrial waste water, domestic waste water and effluent of farmlands.

The concentration of dissolved oxygen in the lagoon is very low. Therefore, hardly any fish can survive in this water. For that reason, an intervention in the current situation is advisable.

7.7. Discussion

To better understand the problems regarding water quality in the lagoon, and especially the main basin, conducting more research is advisable. The water quality should be monitored in a structured way, to increase knowledge about temporal differences over a year.

The behaviour of the DO concentrations due to algal activity in the main basin of the lagoon in the course of a day cannot be analysed from the measured data. In order to analyse this algal activity, hourly measurements need to be taken in the main basin of the lagoon.

No analysis has been done on faecal coliforms. The high nutrient values may indicate a high concentration of faecal coliforms. Asmah et al. (2008) reported that concentrations are higher than recommended values for surface water. As the water quality as a whole has deteriorated in the past years, it is probable that the concentrations of faecal coliforms are currently even higher. This may be hazardous to public health and should be kept in mind, especially if the lagoon will serve as a recreation site in the future.

Furthermore, the possibilities of treating the water flowing into the lagoon have to be investigated. The water quality in the basin can benefit greatly from an improvement in the quality of the inflowing water.

8
Stakeholders

In this chapter, important stakeholders will be discussed. First, an overview of all stakeholders is presented. Institutions that provided important information on the lagoon are also listed. Furthermore, the stakeholders are mapped based on their interest and power. Finally, recommendations for interaction with each stakeholder in order to achieve improvements in the water quality of the lagoon are presented.

8.1. Method

The stakeholders were approached in various ways. Most of the information is exchanged during meetings with representatives of the institutions. Some information is gathered through communications with people that were not necessarily affiliated with the institutions. This knowledge is complemented with information found on the internet.

8.2. Overview

The institutions affiliated with the Sakumo lagoon are listed below. At the top are the bigger governmental organisations, going down in the list the stakeholders get smaller and less well organised.

Ministry of Water Resources, Works and Housing The Ministry of Water Resources, Works and Housing (MWRHW) was recently divided into the Ministry of Works and Housing (MWH) and the Ministry of Water Resources and Sanitation (MWRS).

Ministry of Works and Housing The MWH is responsible for formulating and implementing policies for sectors within Housing and Works. This includes infrastructure and housing. Their goal is to provide people a with safe environment to live in, which contributes to the nation's development (Ministry of Water Resources, Works and Housing, 2015a).

In the Sakumo lagoon, encroachment is a big problem. The MWH is responsible for keeping people out of the floodplains of the lagoon, as this is not a safe place to live during the wet season.

Ministry of Water Resources and Sanitation The MWRS is responsible for formulating policies for sectors within water supply, sanitation and hydrology. For the people around the lagoon, they are to provide safe living conditions with regard to floodings and sanitation (Resource Centre Network Ghana, 2018).

The *Hydrological Services Department* (HSD) used to be an agency of the MWRWH, but is an agency of the MWRS since the division. It is responsible for monitoring and evaluation of flood risk from surface water bodies and coordinates coastal and storm drain works in Ghana (Ministry of Water Resources, Works and Housing, 2015b).

The predecessor of HSD installed the original culvert in the Sakumo lagoon. HSD itself was responsible for the construction of the storm drain in 1997. It is also responsible for the ongoing channelisation of the tributaries that lead into the lagoon, a project which started in 2013 (O. Minkah, pers. comm.).

HSD has assessed the flood risk in the Odaw basin as part of a World Bank project in 2017/2018. The flood risk assessment of the Sakumo basin is one of their plans for the near future.

Ministry of Lands and Natural Resources The Ministry of Lands and Natural Resources (MoLNR) has the responsibility to ensure the sustainable management and utilisation of Ghana's land, forests and wildlife resources (Ministry of Lands and Natural Resources, 2016). Several commissions are part of this ministry.

Forestry Commission The Forestry Commission is an umbrella organisation embodying the various public bodies and agencies that were individually protecting, managing and regulating forest and wildlife resources. They are responsible for the conservation and management of those resources (Forrestry Commission of Ghana, 2018).

The *Wildlife Division* is one of the three divisions of the Forestry Commission. It is also an agency of the Ministry of Lands and Natural Resources. It is responsible for all wildlife in the country and therefore also administers the Sakumo Ramsar site. Its objective is to ensure conservation, management and development of wildlife in Ghana for the benefit of society (Forrestry Commission of Ghana, 2018).

The Sakumo lagoon is a Wetland of International Importance (Ramsar Site). The Wildlife Division is the *Ramsar Administrative Authority* in Ghana. In this role, they are responsible for developing a detailed Action Plan that corresponds with the principles, objectives and expectations of a thoroughly revised National Wetlands Conservation Strategy, with the aim of enhancing its implementation. However, falling under the Ramsar convention has no legal status for the protection of the Ramsar sites in Ghana (The Ramsar Convention Secretariat, 2014).

Ministry of Fisheries and Aquaculture Development The goal of the Ministry of Fisheries and Aquaculture Development (MoFAD) is to develop the fisheries sector as a viable economic segment that will contribute to the development of Ghana (Ministry of Fisheries and Aquaculture Development, 2018). The Sakumo lagoon used to provide jobs for hundreds of fishermen (Local fishermen, pers. comm.). Since the introduction of the invasive plant species, most of these fishermen lost their jobs. It is in the interest of the MoFAD to make the Sakumo lagoon viable for fishing once again.

Ghana Irrigation Development Authority Ghana Irrigation Development Authority (GIDA) is an autonomous government organization which is responsible for irrigation infrastructure for agricultural growth. It has the task to plan, execute and maintain irrigation schemes.

The Ashaiman irrigation scheme for which GIDA is responsible is located just upstream of the lagoon. This dam discharges the excess irrigation water in the Dzorwulu stream leading towards the lagoon (Ghana Irrigation Development Authority, 2018).

Water Research Institute The Water Research Institute (WRI) is a research institute of the Council for Scientific and Industrial Research (CSIR). It is partly privately managed and partly managed by representatives of selected ministries. The WRI conducts research into water quality to provide scientific information and strategies toward the development and management of water resources in Ghana. This research is done in support of socio-economic advancement of the country, focusing on the agriculture, health, industry, energy, transportation, education and tourism sectors (Water Research Institute, 2011).

The WRI has done several investigations on the Sakumo lagoon and other lagoons in Ghana, particularly regarding fish population and pollution. Currently, a long-term investigation is being performed of the water quality and fish population of the Sakumo lagoon. The results have not been published at the time of writing. They will most likely provide better insight in the long term trends of the water quality in the lagoon.

Water Resources Commission The Water Resources Commission (WRC) has the mission to regulate and manage the utilization of water resources, and co-ordinate relevant government policies in relation to them. The WRC is an umberella commission consisting of representatives of amongst others HSD, GIDA, WRI, GMET and the Forestry Commission (Water Resources Commission of Ghana, 2018).

Tema Municipal Assembly The Sakumo lagoon is located in the Tema Metropolis District. Within the municipality of Tema, the Tema Municipal Assembly (TMA), has the most governing power and is responsible for making and enforcing laws.

Tema Development Corporation The Tema Development Corporation (TDC) is responsible for the planning, layout and development of the Tema area. This includes the construction and servicing of residential, commercial and industrial utilities such as roads, public buildings, houses, sewage and street lights (TDC Development Company Limited, 2017). Since the Sakumo lagoon is located partly in the Tema area, development in this area is the responsibility of the TDC.

Sakumono Assembly Sakumono is a small fishing village located directly west of the lagoon. Before the influx of the invasive plants, hundreds of fishermen from this area used to rely on fishing in the lagoon as their income. The lagoon was also used for other purposes, such as for cleaning, drinking water and recreation. The Sakumono Assembly is an electorate that acts as representative for the villagers.

Residential communities Many people live around the lagoon and the main tributaries of the lagoon. The lagoon is used as source of food and income, while the flood plains are used as farmland.

The communities have started building houses in increasing proximity to the lagoon, including in places where it is not allowed. This poses a danger for them and for surrounding people since these houses become flooded after severe rainfall events. Furthermore, the houses in the flood plains hinder the flow through the lagoon, worsening the floodings.

Nearby Industries Some pollution in the lagoon supposedly comes from the nearby industries discharging their untreated waste water upstream of the lagoon or in the lagoon itself. A Coca Cola bottling factory and a presently disused sewage treatment plant are a small pick of the industries located in the vicinity to the lagoon. These industries discharge their waste water into the lagoon. (Agbemehia, 2014) (van Stiphout, 2002)

Other Institutions Alongside the abovementioned direct stakeholders, there are also some indirect stakeholders. They do not directly benefit or experience disadvantages from the situation in the lagoon, but they can help identify or solve problems related to the lagoon. Furthermore, they are a good source of information.

Ghana Meteorological Agency The Ghana Meteorological Agency (GMET) is a government organisation providing meteorological information by collecting, processing and archiving data. GMET gathers meteorological data, such as rainfall and evapotranspiration, at various measuring stations in Ghana (GMet, 2016). The measuring stations in Tema and Accra Airport have been very useful for this particular study of the Sakumo lagoon.

University of Ghana The University of Ghana has many departments, centres and institution which have aided in gathering information about the Sakumo lagoon.

At the Department of Marine and Fisheries Sciences, a lot of historical research has been done on the water quality and fish populations of the Sakumo Lagoon. The Center for African Wetlands contributes to the preservation of African Wetlands, including the Sakumo lagoon. The Regional Institute for Pollution studies trains specialists in water quality issues and is doing research on the water levels in the Sakumo lagoon.

8.3. Analysis

As part of the stakeholder analysis, a stakeholder map has been made. The stakeholder map provides insight into the power and interest of each stakeholder. The interests of stakeholders and how they can be engaged in re-designing the lagoon is described in table 8.1. The stakeholder influence-interest grid shows the relative power of the stakeholders.

Table 8.1: Stakeholder map

Stakeholder	Important to the stakeholder	Strategy of engaging stakeholder
MoWH	Preventing the forming of slums	Propose a project of new living space near Tema, preferably high density residential areas (high-rise)
MoWRS	Connecting houses to the sewage system, constructing a wastewater treatment plant for a more hygienic environment	Propose a project of connecting houses to new or existing sewage and re-launch the waste water treatment plant near Tema
MoLNR	Protect the lagoon, keeping the lagoon suitable for all kinds of birds	Invest in monitoring water quality, press for improved water treatment
MoFA	Providing and maintaining suitable fishing grounds	Press for improved waste water treatment, remove plants from the lagoon
TMA & TDC	Stopping encroachment, improving sewage system, stopping waste dumping	Realise improved housing and sewage systems, prioritise stopping encroachment.
HSD	Preventing flood events	Engage in discussion on how the lagoon can be redesigned.
GIDA	Providing upstream farmers with enough water	Engage in discussion on what they could do to improve the distribution and quality of water
WRI	Improving the fish yield and water quality of the lagoon	Monitor the water quality of the lagoon
WRC	Maintaining and regulating water resources	Engage in discussion on how the lagoon has to be managed
F	Being able to catch enough fish to support family	Engage in discussion on how the lagoon can be made suitable for fishing
Rc	Having a safe place to live	Press for facilitated relocation
I	Having a high production at the lowest costs possible	Make sustainability a marketing strategy, put effort into waste water treatment

8.3.1. Influence-interest grid

The influence-interest grid shows the most important stakeholders and their levels of influence and interest. The Ministry of Lands and Natural Resources is merged with its subdivisions, being the Forestry Commission with its Wildlife Division and Ramsar Administrative Authority. The Tema Municipal Assembly and Tema Development Corporation are merged because they have the same goal, being the development of Tema. The influence-interest grid has been made through estimating the influence and interest of each stakeholder.

Furthermore, it has been determined whether the stakeholders hold a positive, negative or neutral stance towards improvement of the lagoon. Most stakeholders have been judged as neutral, as they do not have a very high interest in changing the lagoon, have other priorities or insufficient funds. Both GIDA and Nearby Industries have been judged as negative, because the aim for improvement of the lagoon could give rise to more stringent legislation for discharging pollutants, for example fertilizers. This could cost these organizations money. The stakeholders with a positive stance to improvement of the lagoon are the fishermen, the Ministry of Lands and Natural Resources, the Ministry of Fishery and Aquaculture and the Water Research Institute. They want better conditions for fish and wildlife, while not experiencing any drawbacks as to an improved state of the lagoon.

It should be noted that the various stakeholders have only minor differences in goals and tasks. For example, the WRC, the WRI and GIDA all have the purpose to monitor and plan structures for the provision of water, with the purpose of this water as the only differing factor. It could be cost effective if those organisations collaborate or merge, to have more power.

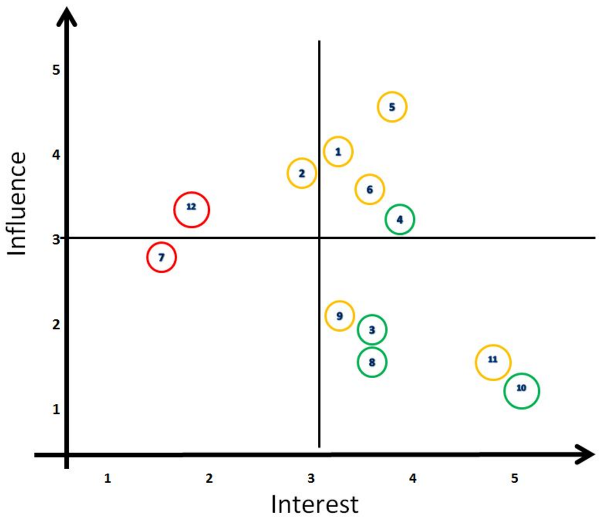


Figure 8.1: Influence-interest grid

Table 8.2: Stakeholders with numbers and abbreviations corresponding to the stakeholder map in figure 8.1

1	MoWH	Ministry of Works and Housing
2	MoWRS	Ministry of Water Resources and Sanitation
3	MoLNR	Ministry of Lands and Natural Resources
4	MoFA	Ministry of Fisheries and Aquaculture
5	TMA & TDC	Tema Municipal Assembly and Tema Development Corporation
6	HSD	Hydrological Services Department
7	GIDA	Ghana Irrigation Development Authority
8	WRI	Water Research Institute
9	WRC	Water Resources Commission
10	F	Fishermen
11	Rc	Residential communities
12	I	Nearby Industries

From the influence-interest grid, it becomes clear that not one single party has both the power and need to come up with improvements for the lagoon. This means that stakeholders will have to work together to improve the water quality in the lagoon.

8.4. Conclusion

Many parties are involved in the well-being of the lagoon. This makes gathering information and implementing possible solutions a difficult task. Furthermore, responsibilities for different aspects of the lagoon lay with different institutions, which even further increases the complexity of the situation. Possibilities for stakeholders to cooperate are present, but the lagoon is not a priority of many organisations. To solve the problems of the lagoon, its health should be prioritised.

The influence-interest grid and the stakeholder map provided in this chapter can be used as the first step to an integrated approach for the improvement of the Sakumo lagoon. The interests of each stakeholder should be taken into account in making decisions on the future of the lagoon.

9

Design alternatives

In this chapter, engineering solutions for redesigning the mouth of the lagoon are proposed. Redesigning the mouth of the lagoon could pose beneficial to the water quality and health of the lagoon. First, options for redesigning the mouth of the lagoon will be presented, each with their own impact on the lagoon system. For each of the options, the implications and impact will be discussed and analysed. The aspects that will be analysed are flood safety, water quality and sediment outflow.

9.1. Structures

To ensure in- and outflow of water to and from the lagoon while still meeting infrastructure demands, one or several structures will be needed in the mouth. Two main options are considered: a channel and a culvert structure. A few variations of both design options will be proposed and evaluated on a number of criteria, such as feasibility, hydrological and ecological impact on the lagoon and aesthetical attractiveness.

9.1.1. Channel

Typically, a lagoon is connected to the adjacent sea by one or multiple channels. These can either be naturally formed or man-made. Naturally formed channels have a tendency to move over time, due to erosion and sedimentation. Man-made (or man-altered) channels typically have a more stable location due to fortification of the embankments. In the case of the Sakumo Lagoon, where a coastal road crosses the mouth of the lagoon, a man-made channel would therefore pose a more suitable solution. A bridge would then be needed to cross the channel in order to maintain the coastal road and rail road. This would significantly increase the costs of construction, since bridges normally take long to build and require a lot of manpower (Hasan, 2018).

Embankments In order for the channel to be stable, i.e. remain in place, the embankments need to be fortified. This can be done using revetment structures, such as concrete lining or rubble slopes. Both of these options will briefly be discussed.

Concrete lining Concrete channel linings come in several varieties. They can be constructed as straight walls or as angled slopes, consist of multiple elements or be constructed in one piece using form work. Smooth concrete linings cause less friction, which makes them suitable bank protection for use in (irrigation) channels. Concrete elements cause more friction and therefore absorb more wave energy, which makes them more suitable for bed protection in wave-heavy conditions.

Rubble slope A rubble slope is a revetment type that consists of an angled slope made up of large rocks or rubble. This rubble protects the adjacent land against erosion from water flow and wave action. As a revetment, rubble slopes are relatively easy to build and can be cheap if material is readily available (Gerrit Jan Schiereck, 2012). A rubble slope alone is not enough to guarantee protection against erosion. Some form of filter is needed to prevent erosion of the hinterland. This can be done by using geotextile or several layers of gravel. The characteristics of the underlaying material, such as grain size and type, should be assessed in order to decide which of these options is most feasible.

Bridge As stated before, a channelised mouth would need a bridge in order to maintain the coastal road. A detailed design for such a bridge is outside of the scope of this report.

Should the bridge need pylons that reach into the channel, these would have to withstand erosion from in- and outflowing water and wave action from the sea, as well as chloride attack due to seawater exposure. Appropriate measurements to account for these phenomena should be taken, such as sufficient concrete cover to limit seawater intrusion and coarser aggregates for the exposed parts of the pylons to limit erosion. When these criteria are implemented sufficiently, the structure would require limited maintenance.

It is unclear wether the bridge should accommodate two or four lanes of traffic. It is still unknown what the effects of the harbour expansion will be on traffic crossing the coastal road. A possible sollution to this problem could be to construct a 2x1 lane bridge first. Then, if the traffic load increases to a point where two more lanes would be needed, a second 2x1 lane bridge can be constructed, making for a total of 2x2 lanes. This would significantly reduce the initial construction costs.

Examples Examples of man-made lagoon outlet channels can be found in the Los Peñasquitos Lagoon and San Elijo Lagoon. Both of these lagoons are located just north of San Diego in California, USA.

The mouth of the Los Peñasquitos Lagoon (shown in figure 9.1a) features a 100 m long concrete bridge, supported by four pylons. On either side of the lagoon mouth, rubble scour protection is applied.

The San Elijo Lagoon has a similar, but smaller opening, along with a bridge that spans 50 m. It is shown in figure 9.1b. At either side of the opening, straight concrete walls serve as abutments.

(a) Bridge crossing the mouth of the Los Peñasquitos Lagoon in California, USA. Photo by Safdie Rabines Architects (2017)

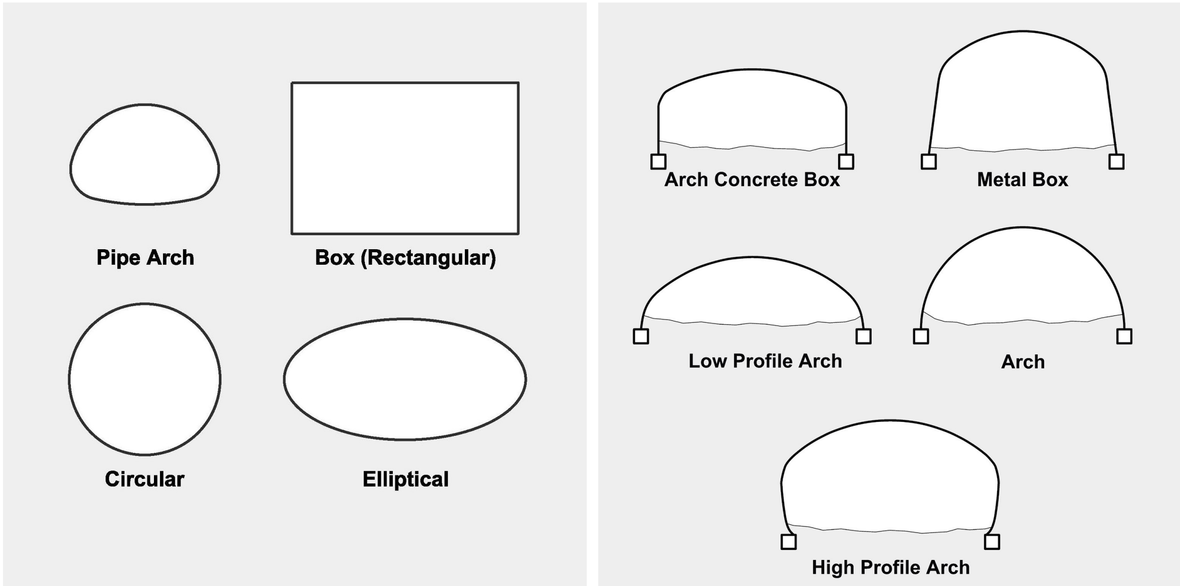
(b) Bridge crossing the mouth of the San Elijo Lagoon in California, USA. Photo by Coastal Environments (2017)

Figure 9.1: Examples of channelised lagoon mouths with bridge crossings.

9.1.2. Culvert

Being the current design solution, a new culvert structure could pose as a viable design option. It would allow exchange of water through the dike, while enabling the road to pass over. A culvert is a simple structure that can generally be built in a short timespan with little manpower, making them relatively cheap (Hasan, 2018).

Shape Culverts come in many different shapes and sizes. These shapes can be divided in closed conduit and open bottom culverts, shown in figure 9.2. They each have their own characteristics for flow and sediment transport. The construction of all of these shapes could either be done using prefabricated elements or in-situ cast concrete.



(a) Closed conduit (b) Open bottom

Figure 9.2: Common used closed conduit and open culvert shapes. Image by Schall et al. (2012)

Sluice gates During dry parts of the year, it might be beneficial to close off the lagoon mouth to the sea in order to retain a certain water level. When using a culvert structure, this can rather easily be accomplished using sluice gates. The current culvert used to include sluice gates, as stated in section 3.1.1. However, sluice gates drive up the costs of design and construction significantly. Should they be automated, cost will be driven up even further. Costs of maintenance would increase significantly as well, since movable parts of structures generally require a lot more maintenance than immovable parts.

9.2. Flood safety

In this section, the flood safety in case of implementing the alternative designs for the mouth of the lagoon will be assessed. In the current situation, water can only flow out of the lagoon via the culverts and storm drains. During heavy rainfall events, water levels in the lagoon will rise because water cannot flow out of the lagoon unhindered. Various designs of the mouth of the lagoon will be assessed, analysing how they influence the flood safety of the area.

A once in 50 year rainfall event will be assessed. This event is chosen since a redesign of the mouth of the lagoon will most probably be designed for a lifetime of 50 years. A once in 50 year event has a large probability of occurrence during this lifetime.

Different mouth designs will be compared with regards to flood safety based on this once in 50 year rainfall event. The mouth designs assessed are culverts of various size and open connections with the sea of various widths, representing a channel with possible sand dune. The culvert and open connection will be placed at two locations in the current coastal road, shown in figure 9.3.

9.2.1. Model set-up

For the flood safety analysis, the SOBEK model described in chapter 5 is used. The model has been run for the entire Sakumo catchment for a once in 50 year rainfall event. This run provided the inflow into the Sakumo lagoon for this rainfall event. The results can be seen in section 5.3. Subsequently, the small model was used to assess the various mouth designs. For this, the discharges into the lagoon are set as upstream boundary conditions. Using this method, different mouth designs can be assessed with a significantly reduced computation time.

9.2.2. Culvert: current and enlarged

First, the water levels in the lagoon area for the current situation are compared to a situation where the culvert cross-section is enlarged. The model is run for a once in 50 year rainfall event over a period of

Figure 9.3: The two possible locations of the mouth of the Sakumo lagoon

20 days. One simulation was done for the current situation, and one with a culvert cross-section three times as large.

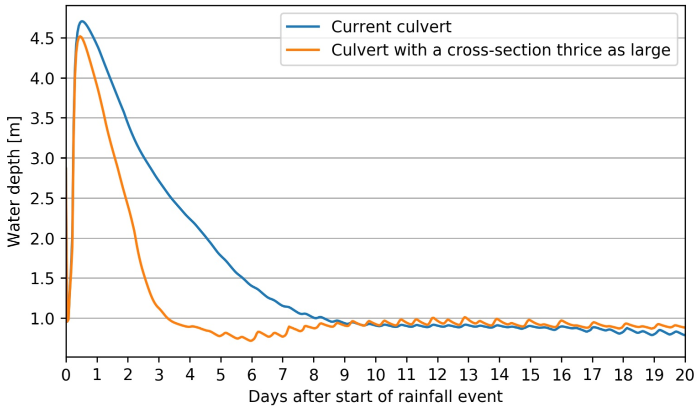


Figure 9.4: Comparison of water depths in the main basin of the lagoon for the current culvert and a culvert with a cross-section three times as large

Figure 9.4 shows the water depth in the basin for the current situation and in a situation with an enlarged culvert. It can be seen that the flood duration reduces significantly when the cross-section of the culvert is increased. Instead of 9 days, it only takes 3 to 4 days to reach the steady state water depth in the basin after the rainfall event. Remarkably, the maximum water depth in the basin does not differ much between the two cases. Instead of a water depth of 4.7 m, a water depth of 4.5 m is reached with the enlarged culvert. Increasing the cross-section of the culvert thus decreases the flood duration, but it barely decreases the maximum water level.

9.2.3. Open connection

Second, the situation with a larger and more natural opening will be assessed. This can be interpreted as the situation in which a bridge is built and the area underneath it is available for the water to flow out. It can either be a natural sand dune or a concrete channel, as for the flood safety assessment these options are interchangeable. The opening will be modelled as a 1D element: a channel with a rectangular cross-section. Three different widths of the opening will be analysed. They will be 10 m, 20 m and 50 m wide. The heights of the cross-sections are set to 20 meter. This way, the water level in the opening has no limit.

The small model is run for a once in 50 year rainfall event over a period of 20 days. The opening is placed both at the current location of the culvert and somewhat further to the west, closer to the main basin.

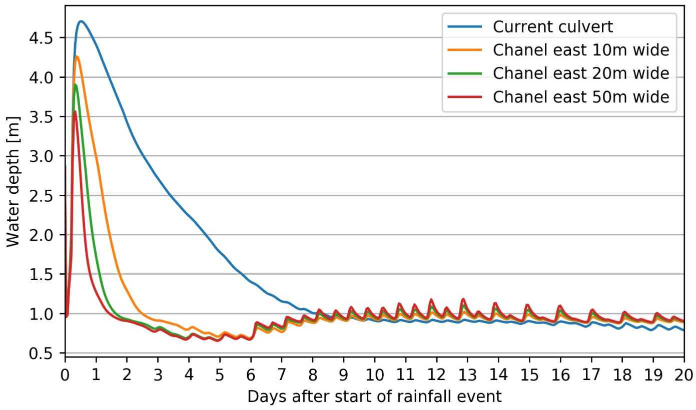


Figure 9.5: Comparison of water depths in the main basin of the lagoon for the current culvert and channels of various sizes connecting the lagoon to the sea

Figure 9.5 shows the water levels in the main basin after a once in 50 year rainfall event for a period of 20 days. It can be observed that, again, the alternative designs affect the flood duration reduces more than they affect the maximum water level. For a 20-50 m wide connection to the sea the flood duration is reduces from 9 days to 1-2 days, a reduction of almost 90 percent. The reduction is far less for the maximum water depth, which reduces from 4.7 m to 3.5-3.9 m, a reduction of only 20 percent.

As mentioned before, an altered location is also assessed. It has been investigated what the effect would be if the connection to the sea would be situated more to the west, closer to the main basin. The water would then have to cover a smaller distance from the main basin to the sea.

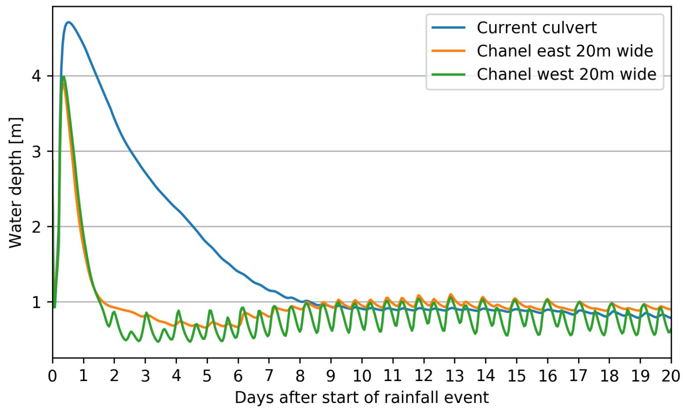


Figure 9.6: Comparison of water depths in the main basin of the lagoon for 20 m openings placed west and east

Figure 9.6 shows the water depth in the lagoon for the original situation and for a 20 m wide opening with the sea both placed east and west. It can be observed that the placement of the opening does not considerably affect the water levels in the lagoon after a flooding. It takes about the same time for the flood to pass and the maximum water levels are also about the same. However, with a mouth placed to the east of the current culvert, the tidal influence in the basin is much greater. The shortened distance from the main basin to the sea causes the tide to reach into the basin much easier.

9.2.4. Pre-1953 situation

Finally, the situation before the construction of the culvert and Accra-Tema road is considered. Before 1953, the lagoon and the sea were only separated by a narrow sand dune which would break through after a heavy rainfall event. The model is again run for a once in 5 year rainfall event for a duration of 5 days. This time, the dune height is lowered to 0.5 m +NLD. The water depth in the basin can be seen in the figure below.

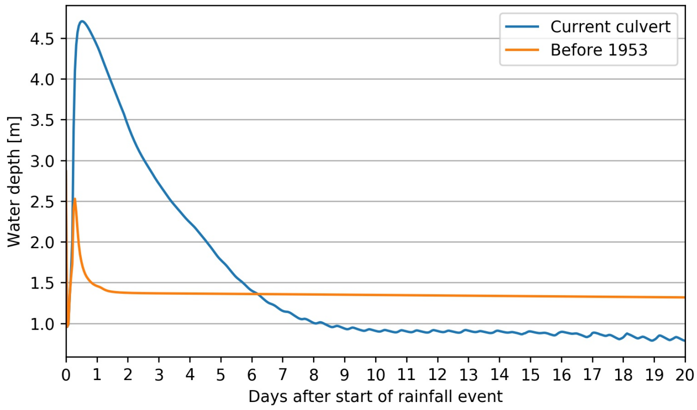


Figure 9.7: Comparison of water depths in the main basin of the lagoon in the current situation and in the situation before 1953

It can be seen that the duration and maximum water depth are much lower than in the current situation. The duration of the flood is in the 1-2 days range. The maximum water depth is around 2.5 m, which about half the maximum water depth in the current situation. However, the sand dune is modelled at a fixed level. In reality, the sand dune would erode during the rainfall event, lowering the crest while the flood progresses. This would then also lead to possible exchange with water from the lagoon and sea. Unfortunately, that effect has not been simulated.

9.3. Water quality

The general idea about designing a different lagoon mouth is to ensure more interaction between the seawater and the water in the lagoon, to reduce residence times and prevent the accumulation of nutrients and other pollutants. In this section the consequences of more interaction between the lagoon and the sea and the pre-1953 situation will be evaluated.

9.3.1. Mixing and flushing

In this section, the effects of the various mouth designs on the mixing and flushing mechanisms in the lagoon will be assessed. The same mouth designs as in the flood safety analysis are analysed. The calculations have been done on dry season conditions, because that is when problems related to limited flushing occur. Several dimensionless numbers and other parameters have been calculated in section 4.4.1, which the results in this section will be compared to.

Because the calculations have been made using crude estimates, the actual values are presumably inaccurate. Therefore, only relative values are presented in this section. In so doing, the design situations can be compared to the current situation.

The results are shown in table 9.1 and 9.2 and will be discussed in this section.

Table 9.1: Relative values of parameters and coefficients

		A_0	v_0	E_0	P_t	N	N_R	D_0	K
Original situation		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Larger culvert		3.00	1.05	3.14	3.14	0.32	0.10	3.14	3.29
East	10 m	3.48	0.97	3.36	3.36	0.30	0.09	3.36	3.53
	20 m	6.97	0.87	6.03	6.03	0.17	0.03	6.03	6.48
	50 m	17.42	0.57	9.92	9.92	0.10	0.01	9.92	10.87
West	10 m	3.48	1.13	3.94	3.94	0.25	0.06	3.94	4.16
	20 m	6.97	1.09	7.61	7.61	0.13	0.02	7.61	8.26
	50 m	17.42	0.86	14.94	14.94	0.07	0.00	14.94	16.65

In which:

A_0 = cross-sectional area of the mouth [m^2]
v_0 = flow velocity at the mouth [m/s]
E_0 = tidal excursion [m]
P_t = tidal prism [m^3]
N = Canter-Cremers number [-]
N_R = Estuarine Richardson number [-]
D_0 = diffusion coefficient [-]
K = Van der Burgh's coefficient [-]

Table 9.2: Relative values of calculated parameters

		L^{HWS}	T_P	N_P	N_Q	N_D
Original situation		1.00	1.00	1.00	1.00	1.00
Larger culvert		0.99	0.32	1.00	0.98	3.16
East	10 m	0.99	0.30	1.00	0.98	3.39
	20 m	0.99	0.17	1.00	0.97	6.10
	50 m	0.99	0.10	1.00	0.97	10.06
West	10 m	0.99	0.25	1.00	0.98	3.97
	20 m	0.99	0.13	1.00	0.97	7.71
	50 m	0.99	0.07	1.00	0.96	15.20

Salt intrusion length The the salt intrusion length at high water slack L^{HWS} provides an indication of the distance over which the sea water intrudes into the estuary. As can be seen in table 9.2, the salt intrusion length does not differ for the various designs.

Flushing time The flushing time is given by T_P, which is the theoretical time scale of the replacement of the total water volume by the tide. This characteristic time scale decreases significantly for the alternative designs. A shorter flushing time scale implies more efficient flushing, which is beneficial for the water quality of the lagoon. As can be seen in table 9.2, each of the alternative mouth designs would decrease the flushing time by at least 3 times. Therefore, they are all very good alternatives to the current situation.

Rate of change of salinity N_P, N_Q, and N_D, given in table 9.2, tell something about the impact of several phenomena on the rate of change of salinity. In case of the Sakumo Lagoon, a fast rate of change of salinity is a preferable situation, since the saline water from the sea is clean and therefore able to flush the lagoon.

Firstly, N_P is the overall importance of rainfall for the rate of change of salinity, which does not vary for the various mouth designs.

Secondly, N_Q is the importance of fresh water inflow from the tributaries, of which differences among the various mouth designs are negligible.

Finally, N_D is the overall impact of dispersion related to the tidal forcing in the lagoon. This parameter does vary significantly among the various mouth designs, with the widest channel openings being the most favourable. In those cases, the impact of dispersion on the rate of change of salinity is 10 to 15 times larger than in the current situation. This means that the amount of mixing in the lagoon can be increased greatly through construction of a different lagoon mouth.

9.3.2. Expected effect of tidal flushing

The expected effect of tidal flushing on the water quality is not easy to estimate. Many parameters have to be taken into account to be able to say something about the expected state of the lagoon.

When tidal flushing is increased, the salinity of the lagoon will rise due to the intrusion and mixing of seawater. This can affect current organisms in the lagoon of which the tolerance to salinity is not known. In the current situation, an amount of sea water is entering the lagoon every tidal cycle. It is probable that plants and species in the lagoon have a certain resistance against salinity. However, if a part of the lagoon plants die due to the increased salinity, this will have a negative effect on the water quality. The decay of dead plants will lead to even more eutrophication, which is already a problem in the lagoon. Then again, eutrophication is likely to decrease due to the outwash of nutrients. When phosphorus is washed out the lagoon, the trophic state of the lagoon as calculated in section 7.3 will be lower as follows from the relation with algal biomass.

The influx of seawater will also bring in extra dissolved oxygen. Besides the outflow of ammonium-laden lagoon water, the ammonium concentration will drop due to the decay by nitrification. As ammonium is a toxic substance to many fish species, this process is very important for improving the water quality.

9.3.3. Expected effect of restoring pre-1953 situation

The effect on the water quality of the restoration of the pre-1953 situation is even more difficult to estimate. It is not known if a dike between the lagoon and sea will flood or break and if and how long it will take before the dike restores itself. The tidal flushing is expected to occur only after the breakthrough of the sand dune. How long flushing will take place is estimated to be a few days after the breakthrough. In these days the same processes take place as described under tidal flushing. As this can only take place on limited occasions, the effect of flushing will be lower. The least favourable and for that reason the highest risk of this solution is the fact that the salinity of the lagoon can become very high. Due to the inflow of seawater during spring high tides in combination with high evaporation and low run-off during the dry season, there is a chance that the lagoon can become hyper-saline (Snow and Taljaard, 2007).

9.4. Sediment outflow

Siltation of the lagoon has posed a problem in recent years. When sediment from upstream settles in the lagoon basin, the bottom level increases. The resulting smaller water depths produce smaller flow velocities, increasing siltation rates. In its turn, this facilitates settlement of vegetation. The vegetation increases friction, accelerating the process. An increase in bottom level of the lagoon can cause higher water levels during floods. Furthermore, the water quality can be negatively influenced by this bottom level increase, affecting fish and fishermen in the area. In order to maintain a favourable water depth, the sediment coming from upstream needs to be able to flow out of the lagoon.

In this section, the design alternatives discussed in section 9.2 are assessed, but this time regarding the potential of sediment to flow out of the basin. In order to assess this potential the velocity at the connection of the lagoon with the sea is analysed. Using the Engelund-Hansen sediment transport formulation, an estimate is made of the amount of sediment exiting the lagoon after a once in 50 year rainfall event. These amounts are then compared for all the design alternatives.

The Engelund-Hansen sediment transport formulation is a formulation used for sediment transport in alluvial streams. Using differences in flow velocities, it can be analysed in what parts of an alluvial system erosion or accretion occurs. In this case, the flow velocities at the mouth of the different design proposals are used to derive the corresponding sediment transport rate according to the Engelund-Hansen formulation (Engelund and Hansen, 1967). The sediment transport rate can then be compared for the different design alternatives.

The Engelund-Hansen formulation is given as:

$$S = B \cdot m \cdot u^n \tag{9.1}$$

With:

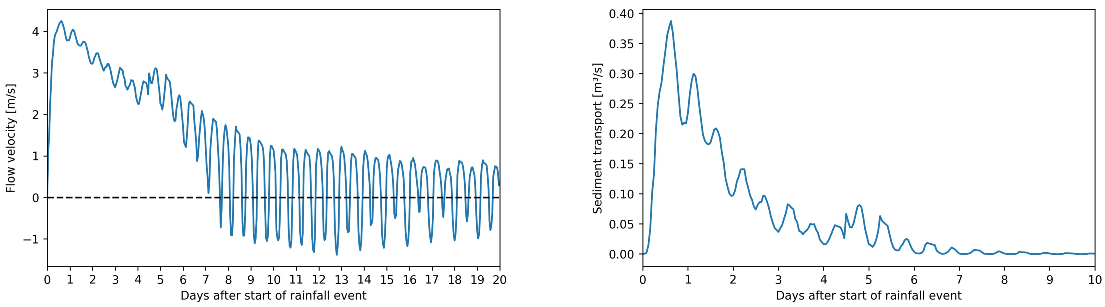
S	=	sediment transport rate [m^3/s]
B	=	width of channel [m]
u	=	flow velocity [m/s]
m	=	coefficient equal to 1 $\times 10^{-4}$ [-]
n	=	coefficient equal to 5 [-]

The sediment transport rates are calculated using the flow velocities derived from the overland flow model. The rainfall event with a return period of 50 years is used to compare the sediment transport rates for the various mouth designs. The sediment transport rate is calculated using equation 9.1 for each time step in the twenty-day simulation. Integrating these sediment transport rates over time gives the total sediment transport.

The coefficients m and n are assumed to be equal for the different design alternatives, although this may not be the case in reality. In reality, coefficients m and n are not easily obtained. They are dependent on, among other things, the grain size and bottom friction. The formulation is used to give a rough estimate of the sediment transport for the different design alternatives in order to compare these values to one another. They are unsuitable for providing an estimate on the exact quantity of the total sediment transport. The coefficients must be calibrated for detailed calculations to be performed to compute the exact transport rates.

9.4.1. Results

The velocities at the mouth after a once in 50 year rainfall event in the current situation of the lagoon can be seen in figure 9.8a. It takes a few days for the flow velocities to reach a steady state. In the steady state, water is flowing into the lagoon during high tide and out during low tide. Immediately after the rainfall event, the flow velocities are four times as high as in the steady state. According to the Engelund-Hansen relation, this should lead to sediment transport rates that are a factor 4^5 times higher. Figure 9.8b shows that this in indeed the case. Sediment transport is almost negligible in the steady state compared to the transport during the flood. In the days after the rainfall event the sediment transport is in the 0.1-0.4 m^3/s range.



(a) Flow velocity

(b) Sediment transport rate

Figure 9.8: Simulation results of the flow velocities and corresponding sediment transport rates at the culvert after a once in 50 year rainfall event, current situation

Taking the area under the graph in figure 9.8b gives the total sediment transport in the simulation period. This is also done for the other design alternatives. This way, a comparison can be made for the sediment discharge for the different designs. The results can be seen in table 9.3.

Table 9.3: The total sediment transport through the mouth for different alternatives compared to the original situation after a once in 50 year rainfall event

Situation	**Relative sediment transport** $^{S}/_{S_0}$
Original	1.0
3x larger culvert	4.3
10 m wide opening east	13.9
20 m wide opening east	14.3
50 m wide opening east	6.0
10 m wide opening west	10.4
20 m wide opening west	10.4
50 m wide opening west	4.6

Table 9.3 shows that larger and wider openings generally lead to more sediment flow out of the lagoon after a heavy rainfall event. A culvert with a cross-section three times as large as the original one, can discharge more than four times as much sediment after a heavy rainfall event.

It has to be noted that a higher sediment transport rate does not necessarily mean that the flow velocities are higher than in the original culvert. The combination of the flow velocity, duration of the outflow and the width of the culvert lead to a sediment transport over 20 days that is 4.3 times higher than originally.

Even more sediment can be discharged when the lagoon is connected to the sea with a 10 m or 20 m wide channel. This amount reduces again for the 50 m wide channel. This can be explained by the lower flow velocities, decreasing the sediment transport capacity.

When the channel is placed to the west of the current culvert, the sediment transport capacity is slightly less than the east options. This is due to the fact that the flow velocities in the channel are lower when it is placed to the west. An explanation for this could be that the distance that the water has to travel to the western location is smaller, making the water reach the point earlier than it would reach the eastern location. This allows the water to flow out of the basin more easily, distributing the total water volume over a longer period of time. This reduces the peak velocity, subsequently reducing the peak sediment transport rate.

9.5. Conclusion

A culvert structure that is three times larger than the current culvert is likely to be the cheapest option. It also shows improvements to both flood safety and flushing, shortening both flood duration and flushing time. A significant increase in sediment outflow can also be observed. Even larger culvert structures could be investigated.

A channel with bridge is usually more expensive to build than a culvert. However, this option does prove to be more effective in reducing flood duration and flushing time than the larger culvert that was modelled. Furthermore, the channel should not be too wide, as a wider channel would be less beneficial to sediment outflow. Finally, an advantage of a channel is that it can be made to look natural with rubble slopes. This would make for a more appealing area for tourism.

Moving the outflow opening to the west has some advantages and disadvantages as well. It increases flushing, while decreasing sediment outflow, with little to no effect on flood safety.

10
Conclusions and recommendations

In this chapter, the results of all aspects of this research are combined. The major problems of the lagoon are summarised, after which an explanation is given on if and how these problems can be solved through redesigning the lagoon mouth.

10.1. Conclusions

Both the lagoon itself and the structures that form the lagoon mouth are in a bad shape. The concrete culvert has eroded at the sea side of the lagoon and the characteristics of the water in the lagoon resemble raw sewage water more than natural surface water. An intervention in the current state of the lagoon and its structures is crucial for making use of its potential value for fishery, tourism, ecology, and to maintain the flood safety of the road over and the surroundings of the lagoon.

A new culvert can be realised fairly easily. The effect of salt on concrete should be taken into account, which may have not or minimally been done for the current structure. A change in size of the culvert can provide for shorter residence times in the lagoon resulting in a better water quality. If the aquatic life in the lagoon does not suffer from the introduction of more salt, this would be beneficial to the ecology in the lagoon.

Another solution is removing a part of the dike between the lagoon and the sea, and replacing it with a bridge over the lagoon mouth to maintain the coastal road between Accra and Tema. A sand bar will then form under the bridge which keeps the lagoon separated from the sea in drier times. In the wet season, this sandbar breaches to discharge water to the ocean. This solution can potentially bring the hydrodynamics of the lagoon back to their natural state, as it was before 1953.

10.1.1. Considerations

Various solutions have been designed to enhance water quality. These engineering solutions cover only a change in layout of the lagoon mouth. Other solutions, in which the focus is on taking away the source of the problem, are not taken into account in this research but should not be disregarded.

The most straightforward way to achieve better water quality in the lagoon is to limit the inflow of pollutants. In section 7.5, possible causes of the water quality degradation have been discussed. One of these causes was the inflow of domestic waste water from the nearby communities. Limiting this inflow can be achieved by connecting houses to a sewage network or by construction of a treatment plant north of the lagoon to sanitise the water coming from the city drains. In this way, the pollution through domestic waste water entering the lagoon is brought to a minimum. Connecting houses to a sewage network consumes a lot of time and resources. Construction of a treatment plant is complicated, as the plant has to be close to the city drain channels, which already experiences complications with flooding during the wet season

In addition to improving the quality of the inflowing water, it is probable that that dredging the lagoon will also improve the water quality in the basin. The sediment covering the bottom of the lagoon may contain a lot of nutrients which will eventually dissolve into the lagoon. This makes flushing of the lagoon much less efficient because new nutrients will be instantly available from the sediment.

10.2. Recommendations

On the governmental level, progress can be achieved. Cooperation between stakeholders can create a better system to monitor the water quality in the lagoon. Conclusions in this report are largely drawn on sparse datasets or even rough estimates. Monitoring the water quality is necessary for accurately determining how fast the lagoon is deteriorating. Furthermore, this can provide more insight into the contributions of different polluters. Legislation can then be adjusted accordingly.

Moreover, investing in sanitation to reduce domestic wastewater discharging into the lagoon would be helpful. Along with this, effort should be made to decrease the amount of solid waste ending up in the lagoon. For this, it is necessary to raise awareness among the communities of the impact of both solid and liquid waste to their surroundings.

10.2.1. Decision making

To be able to make a well-founded decision on the favourability of a design alternative, the interests derived from the stakeholder analysis should be taken into account.

One of these interests is to find a way in which fishermen can use the lagoon as fishing ground again. To achieve this, the invasive plants have to be removed and a minimum level of dissolved oxygen is needed. Eutrophication, if not too severe, is not a big problem for fish and can be even beneficial if a lot of algae and thus food for the fish is available.

Another interest is to increase the recreational value and biodiversity within the lagoon. There are possibilities to develop the tourism industry in this area. For doing so, the lagoon would need to be more aesthetically attractive. Additional to the adjustments necessary for the fishing interest, the amount of nutrients and other pollutants in the water should also be reduced. This can be achieved by increasing the flushing in the lagoon as well as controlling the waste water discharge as explained in section 10.1.1.

II

Klottey Lagoon

11 Introduction

In the second part of this report, the Klottey lagoon and Marine Drive area will be assessed. In this introduction, a brief overview of the lagoon is given, followed by the background of study. This is followed by the problem statement and an outline of this part of the report.

11.1. Overview

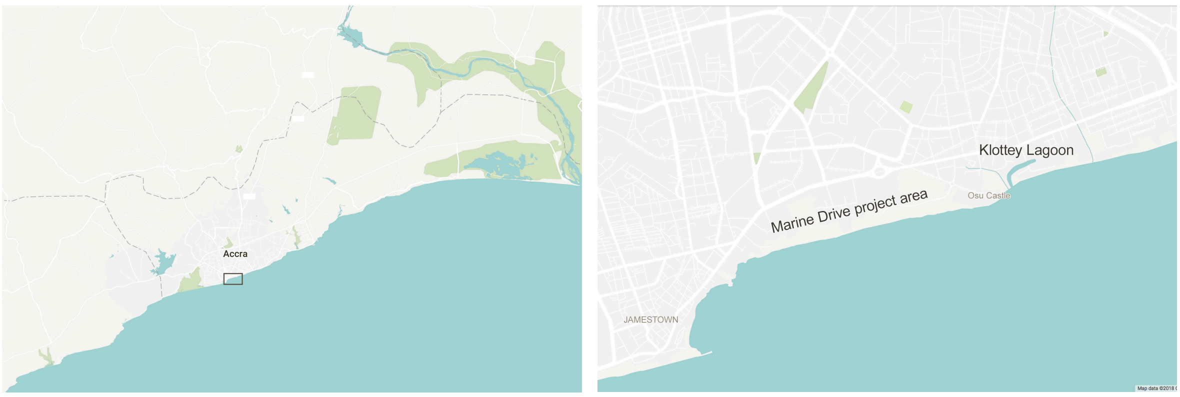


Figure 11.1: Overview of the location of the Klottey lagoon and Marine Drive Project area

The Klottey lagoon is located in the centre of the Ghanaian capital of Accra. The Klottey lagoon lies east of the former presidential office, the Osu Castle. Its main basin is located at coordinates 05°32'56"N, 0°10'51"W. With an area of only 7500 m^2, it is a small lagoon that is located in a very densely populated area. On the other side of the Osu Castle is the Marine Drive project site. This is a large piece of land that is designated to be a future tourist development area.

11.2. Background of study

Ghana has one of Africa's strongest economies. The current stability and prosperity attracts a fair amount of tourists every year. Some of those tourists visit Ghana to enjoy its coastline. Ghana's capital is conveniently located next to the shore, but it does not utilize this potential advantage yet. Tourists that want to enjoy the coast to its fullest prefer destinations outside of Accra. The Marine Drive project was set up to change this.

The Marine Drive project is set up to enhance the attractiveness of the Marine Drive for tourists. The Marine Drive is a piece of land located along the beach bordering the vibrant city centre. There are plans to construct a wide variety of hotels, beach resorts, casinos and other tourist attractions. A sea defence structure will be constructed in order to maintain the beach front.

At the same time the Klottey Lagoon, located to the east of the Osu Castle, has been neglected. It is currently in a very bad state regarding its water quality. The lagoon is separated from the sea by a small decaying concrete structure under a small sand dune. After a rainfall event, the water in the lagoon overflows the sand dune and enters the sea. A major city drain is located to the west of the Klottey Lagoon. This drain discharges waste water directly into the sea. A few smaller drains are located on the Marine Drive beachfront.

In the current situation, some of the debris entering the sea from the Klottey Lagoon or the city drains ends up at the beaches along the Marine Drive. In order to make the area attractive for tourists, the beaches should be kept as clean as possible. In this way, health risks can be minimized. Furthermore, debris in the water and on the beaches may discourage tourists from coming to the area.

There are plans to construct a small fishing harbour at the Klottey lagoon site. The harbour will consist of a jetty protruding into the sea, in order to facilitate the unloading of fish while protected from the waves. There will also be a fish market and some restaurants and other establishments, built along the Klottey lagoon.

In addition, many people live in the near vicinity of the lagoon and experience the pollution on a daily basis. Of these people, some are local fishermen that berth on the beach directly to the east of the mouth of the lagoon, and they experience the consequences of the dirty water discharging into the sea. When the alongshore current is directed to the east, the water pollutes the beach where fishermen are unloading their catch resulting in unhygienic circumstances. Fish caught in the near-shore polluted water may also be harmful to public health. In order to minimize the risk of contamination, the water discharged into the sea should be minimally polluted.

Furthermore, the beaches at the Marine Drive and Klottey lagoon are exposed to wave attack. The beaches are therefore subject to erosion and are already quite narrow. In order to improve the quality of the beaches, a sea defence structure is planned. The sea defence structure is supposed to prevent erosion of the beaches and make the water more suitable for swimming.

This chapter investigates the current state of the area, the impact of the water quality on the future developments and the effect of the future developments on the shoreline.

11.3. Problem statement

The central question that will be answered in this report is:

> *What is the current state of the Klottey lagoon area and how will this affect the Marine Drive and fishing harbour development plans?*

In order to answer this question, a more detailed understanding of the lagoon system is needed. The following sub-questions will need to be answered as well:

1. *What are the governing hydraulic processes of the Klottey lagoon?*
2. *What is the current state of the Klottey lagoon regarding water quality?*
3. *What are the governing processes regarding sediment transport along the coast of the Marine Drive and Osu coastline?*

11.4. Outline

This report will be structured as follows. First, in chapter 12, the hydraulic system of the lagoon is explained to provide an answer on the first sub-question. Then, the current state regarding water quality is explained in chapter 13. In chapter 14, the behaviour of sediment transportation along the coast is explained. Chapter 15 contains some concluding remarks and recommendations.

12

Hydraulic system

An understanding of the hydraulic processes in and around te lagoon is necessary for making predictions of the system response to changes. Therefore, the dominant hydraulic processes will be discussed in this chapter.

12.1. Area and system

A general overview of the area and hydraulic system of the Klottey lagoon will be provided in this section. The dimensions of the lagoon and its catchment will be given, along with information on the climate. From the rainfall in the area, some estimates will be given on the inflows in the lagoon.

12.1.1. Overview

Klottey Lagoon The Klottey Lagoon has an area of about 7500 m^2. After running parallel to the shore for about 200 meters, the lagoon bends off to the south to meet the sea. Three big pipes at the upstream end connect the lagoon to its catchment. At the downstream end, it is connected to the sea through a concrete structure. On top of the bottom slab of this structure, sand has accumulated that closes off the lagoon in the dry season.

(a) The storm drain

(b) View on the basin, looking toward the southeast

Figure 12.1: View on the upstream end of the lagoon

Next to the lagoon mouth, a city drainage channel discharges into the sea. The water of this drainage channel is severely polluted as it serves as a sewage drain. The mouth of the channel is filled with sediment. The water has made a path toward the sea through this layer of sand. The mouth of the city drain also has a discharge structure at the sea side. This structure inhibits the water of the drainage channel from flowing into the lagoon.

(a) The city drain (b) Mouth of the Klottey lagoon

Figure 12.2: View of the downstream end, looking toward the north

Marine Drive Project site The Marine Drive Project Site is located to the west of the lagoon. It spans a beachfront of 2.5 km.

About five drainage streams were seen running over the beach into the sea. The most westward one was most clearly a city drain channel. The others were small streams running over the beaches to the sea. Two of the streams had concrete gutters laying nearby. These gutters are probably old drainage systems, which have broken down over time.

(a) View on the construction site (b) A drainage channel running across the beach

Figure 12.3: View of the Marine Drive beach front

12.1.2. Catchment area of the Klottey Lagoon

The catchment area of the Klottey lagoon was estimated from a Digital Elevation Model (DEM). The flow pattern was simulated from this DEM file using QGIS so that the catchment areas of various streams could be distinguished. This flow map is overlaid on a satellite image of the area in figure 12.4. The surface area was calculated from this flow map. This results in a surface area of 2.3 km^2.

12.1.3. Drainage network Accra

Since the Klottey lagoon is located in a densely populated area in the capital of Ghana, not only the elevation-driven routing of rainfall runoff is important in this system. Man-made drainage structures affect the paths of the flow. In order to determine which areas of Accra drain into the Klottey lagoon and into the city drain next to it, the drainage network is crucial. Unfortunately, no map of this drainage network was available.

Figure 12.4: Flow pattern in the catchment of the Klottey lagoon

12.2. Normal and extreme conditions

12.2.1. Rainfall

Rainfall data were received from the Ghana Meteorological Agency (GMET) for the Accra Airport synoptic station. The dataset has daily rainfall values for the period from February 1944 to November 2015. An analysis of the rainfall events is used to estimate normal and extreme conditions and can be found in appendix C.

Normal conditions Because of the strong seasonality of the rainfall events, the normal conditions are split up into dry- and wet season values. For a normal dry season rainfall event, an estimate of 11 mm in 24 hours is used. The mean total rainfall during the dry season is 74 mm. For a normal wet season rainfall event, an estimate of 83 mm in 24 hours is used.

Extreme conditions An extreme rainfall event is most likely to occur in the wet season and is estimated for several return periods in appendix C. When considering a lifetime of 50 years with a probability of failure P_f = 10 %, a rainfall event of 254 mm is used as an estimate.

12.2.2. Discharge

The rainfall events described in section 12.2.1 produce discharges into the lagoon. These discharges are estimated for both normal and extreme conditions. The estimates are based on the total volume of water that precipitates onto the catchment of the Klottey lagoon, under the assumption that not all water flows into the lagoon. Part of the precipitation is lost to surface storage, interception and infiltration. These factors all decrease the amount of water flowing into the lagoon. It is assumed that during a 24-hour rainfall event, 20 mm precipitation is lost to these factors, while the rest of the water flows into the lagoon.

Area reduction factor The measurements of the Airport Synoptic station are point measurements. Since the amount of precipitation on an area is, on average, less than the amount measured on one point, an Area Reduction Factor (ARF) is necessary to account for this difference. However, since the catchment of the Klottey lagoon is only 2.3 km^2, the ARF will be very close to one. This means that the amount of precipitation on the catchment area will be almost equal to a point measurement. The ARF is therefore neglected.

Intensity The daily precipitation values are not uniformly distributed over a day: every rainfall event has a peak. During or directly after this peak, the largest discharges into the lagoon are found. Unfortunately, the Intensity Duration Frequency (IDF) curve of Accra is not available. Since the Tema and Accra Airport measuring stations are located 20 km apart and fall in the same climate zone, it is assumed that the characteristics of rainfall events of these two locations are similar. An estimation is made on the percentage of the precipitation that falls in a one-hour period. It is based on the data available for the Tema measuring station.

A return period is chosen, after which the 24-hour rainfall event is calculated based on the fitted probabilistic distribution. This daily rainfall value is compared with the 1-hour rainfall value for the same return period, extracted from the IDF curve. This comparison shows that around 50 % of the total daily precipitation is concentrated in a one-hour block. This value will be used to estimate the peak discharge during a rainfall event.

The discharges for the normal and extreme conditions are provided in table 12.1.

Table 12.1: Discharges for various rainfall events

Normal conditions		precipitation [mm/day]	runoff [m^3/day]
	dry season average	0.68	0.79*
	dry season event	11	12*
	wet season event	83	95
Extreme conditions	return period	precipitation [mm/day]	runoff [m^3/day]
	5 years	120	138
	10 years	141	162
	25 years	168	193
	100 years	208	239
$P_f = 10\%$	475 years	254	292
$P_f = 5\%$	975 years	275	316
$P_f = 1\%$	4975 years	323	371

* This is most likely an over-estimation.

12.3. Structures

As explained in section 12.1.1, two concrete structures are situated at the mouth of the lagoon. Both of them are simple canals with rectangular cross-sections. To the west lies the outflow canal of the city drain and to the east lies the outflow opening of the lagoon. It is unclear when these structures were built, but they appear to be quite old. In this section, the state of these structures will be discussed.

12.3.1. City drain

The city drain shown in figure 12.5 is a concrete channel that extends out into the sea. It has a rectangular cross-section and is approximately 6 m wide. At the outflow end, the city drain curves off towards the east by 45°.

The part of the city drain extending into the sea stands on concrete poles, with its concrete bottom slabs hovering over the bed. This can be seen in figure 12.5a. It is likely that these bottom slabs used to rest on or were recessed in the beach, such that the structure ended up in its current elevated position as the beach eroded. Since this is most likely not the intended position of the structure and given its deteriorated state, it may be unsafe. Even more so because local fishermen have been seen to walk on it in order to reach the sea. This means that there is a chance of injury in a case of failure of the structure.

12.3.2. Lagoon opening

The lagoon mouth is located adjacent to the city drain. It is a concrete channel with a rectangular cross-section, shown in figure 12.7. At about 11 m wide, it is somewhat wider than the city drain. It extends less far into the sea than the city drain and has a straight outflow opening. The walls of the lagoon opening extend inland as well, with a length of about 50 m.

There is a small, improvised wooden bridge across the mouth. Beneath this bridge, there are two vertical slots in the concrete wall, one on either side of the channel (see figure 12.6). The exact purpose of these slots is unclear, but they seem to have held a sluice gate that could be operated manually. Currently, a naturally formed sand dune serves as a barrier to the sea, so the sluice gate may have become obsolete.

(a) Outflow end (b) Upstream view

Figure 12.5: City drain near the Klottey Lagoon.

Figure 12.6: Slots in the concrete walls of the mouth of the Klottey lagoon

As the city drain, the lagoon opening also shows signs of concrete deterioration, though not as severe. It only shows signs of surface degradation. Therefore, it does not have equal risk of structural failure as the city drain.

(a) Outflow end (b) Upstream view

Figure 12.7: Mouth of the Klottey Lagoon.

13

Quality and pollution

Water quality of the lagoon is analysed to learn something about the state of the lagoon and the need to intervene in the current situation.

13.1. History

Little literature is available about the Klottey Lagoon. This may be because the area used to be a no-go zone during the military government times (Mr. De Graft-Johnson, pers. comm.). Few reports exists which even mention the Klottey Lagoon. An interview by Penniman (2002) states that the lagoon was surrounded by bushy area in 1997 and that the area was only used for gathering food. A map of Accra in 1997 (Asomani-Boateng and Haight, 1997) confirms that there was not a residential area.

Since no historical information could be found on the water quality, it is difficult to say something about historical trends. Nevertheless, there are reasons to assume that the water quality has been deteriorating. Due to Accra's expansion, people have started living closer to the lagoon and the population density around the lagoon has subsequently skyrocketed. This has definitely contributed to the bad state of the lagoon.

13.2. Current situation

The water in the lagoon is expected to be of poor quality. Untreated waste water enters the lagoon via a city drain. Another major city drain is located next to the lagoon. People have been seen to defecate in or around the lagoon. Furthermore, the lagoon and drains are also filled with debris. Plastic and other dumped materials can be seen everywhere in and around the lagoon.

The surroundings of the lagoon are densely populated. New urban development can also be seen in the vicinity of the lagoon. The water quality is therefore not expected to improve in the foreseeable future.

The current situation is analysed on the following parameters: ammonia-nitrogen (NH3-N), nitratre-nitrogen (NO3-N), ortho-phosphate (PO4), temperature and conductivity. These parameters are chosen because they can provide insight into the trophic state of the lagoon.

13.3. Materials and methods

Samples were taken on 4 different locations in the lagoon. One sample was taken near the mouth, one in the upstream end of the lagoon near the culvert, and two in between. An additional measurement was done in the city drain. Four samples were taken at sea. See figure 13.1 for an overview of these measurement locations.

The measurements were taken on 12 March 2018 between 11:30 and 12:30. At that time, the sand layer was intact and the lagoon was not connected to the sea. However, signs of a recent in- or outflow event of water were visible in the sand bar.

In-situ measurements were performed with a HANNA multiparameter probe. The probe should have been able to measure temperature, pH, dissolved oxygen and conductivity. However, the probe seemed not to function for several parameters. The parameters of which the probe seemed to take

Figure 13.1: Water quality and sediment sampling locations in and near the Klottey Lagoon

accurate measurements are temperature and conductivity. All other measured parameters have been neglected.

In addition to the probe measurements, nutrients were analysed. For this purpose, 500 ml water samples were taken and stored in an ice cooled box. The samples were then analysed in the laboratory. The concentrations of ammonia, nitrate and phosphate were analysed using Hach reagent powder pillow tests. After the reaction with the reagent, the nutrient levels were measured by a spectrophotometer.

The four samples containing lagoon water and the sample containing city drain water had to be diluted for the ammonia and phosphate tests. For analysing ammonia, the samples were diluted to a ratio of 1:100.

13.4. Results

The results of the measurements and sampling analysis will be presented in this section. The values measured in-situ are presented in table 13.1, while the results of the analysis of nutrient concentrations are given in table 13.2. All measurements can be found in appendix E.

Table 13.1: In-situ water quality measurements by location

		Lagoon water			Sea water			City drain
Temperature	°C	33.46	±	1.55	30.82	±	0.04	37.49
Salinity	PSU	8.40	±	5.91	43.95	±	0.17	0.35

Table 13.2: Nutrient concentrations in mg/l by location

		Lagoon water			Sea water			City drain
Phosphorous	PO4	3.18	±	1.74	0.14	±	0.02	20.07
Ammonia	NH3-N	3.12	±	0.53	0.19	±	0.15	38.01
Nitrate	NO3-N	17.35	±	15.76	1.05	±	0.37	36.60

13.5. Conclusion

13.5.1. Temperature and salinity

A temperature gradient was observed within the lagoon. At the upstream end, the temperature was measured at 34.44 °C and gradually decreased progressing to the mouth to a value of 31.42 °C. The salinity increased from 3.21 PSU to 15.98 PSU in this direction, which together with the spatial temperature variation suggests that the water near the mouth was mixed with sea water. This means that there is some exchange in the dry season.

The temperature in the city drain was significantly higher with a value of 37.49 °C. The salinity was low, which was expected as there was a constant flow of water our of the city drain making it difficult for sea water to intrude.

13.5.2. Phosphate (PO4)

Phosphate concentrations were very high in the lagoon and extremely high in the city drain. This is a sign that in the city drain a lot of domestic waste water is present.

Within the lagoon, spatial differences were observed. At the upstream end of the lagoon, the phosphate concentrations were slightly lower than at the mouth. As algae use phosphate to grow, it is possible that this difference in phosphate concentrations is caused by greater algal growth at the upstream side of the lagoon. These algae produce oxygen, which in its turn enables the transfer of ammonia into nitrite and nitrate. The high nitrate concentrations at the upstream end of the lagoon confirm this theory.

13.5.3. Ammonia (NH3-N)

In the lagoon, the ammonia concentrations were far lower than in the city drain. This is presumably the result of the transformation of ammonia into nitrate. This process consumes oxygen which is available in the lagoon because of algal growth.

At sea, one of the measurements peaked at 0.41 mg/l while the other measurements were lower. This was the measurement just downstream of the city drain and the lagoon. This indicates that the water exiting the drain containing high concentrations of ammonia can still be measured at sea.

13.5.4. Nitrate (NO3-N)

Nitrate concentrations differed extremely within the lagoon. In the far east a concentration of 40.8 mg/l was measured. This is an even higher value than in the city drain. In the other 3 measuring locations in the lagoon, values were at least four times lower. It is very likely that the transformation of ammonia into nitrate is the cause of this phenomenon. In the city drain, this process does not take place and for that reason the nitrate concentration is lower.

13.5.5. Overall water quality

The water quality in the lagoon is currently bad, but aquatic life is still possible or easy to bring back to the lagoon. Due to the size of the lagoon it is possible to occasionaly flush the lagoon with a portable pump which can help to keep nutrient levels low. The most problematic feature is the water discharging from the city drain. It is advisable to treat this water first before discharging it into the sea.

13.6. Discussion

All levels of nutrient concentrations were high. The trophic state of the lagoon is probably eutrophic, but the lack of data on dissolved oxygen causes a lack in insight of the exact state of the lagoon. Periodic monitoring of the lagoon is advisable in order to make accurate statements about the water quality. With the concentrations found, it is expected that the DO concentrations in the city drain will be lowest. The amount of oxygen in the lagoon is expected to be high and can possibly reach the point of oxygen saturation because of algal activity.

14

Shore morphology

The sediment transport along the coast of Accra is dominated by wind waves. The bulk net sediment transport is between 500×10^3 m^3/year and 1000×10^3 m^3/year in eastward direction (Giardino et al., 2017). However, this value is an indication since it was provided in a large-scale study of the West-African coast. A sediment transport analysis is done in order to get a better understanding of the sediment transport along the Marine Drive project area and the Klottey lagoon. Finally, the effects of the planned structures, being the sea defence protecting the Marine Drive beaches and the planned fishing harbour, on the shoreline are assessed.

14.1. Field work

In order to get a better understanding of the sediment composition along the coast and possible impact of future structures, sediment samples were taken along a 5 km coastal stretch.

14.1.1. Materials and methods

Sediment samples were taken on Monday 12 March 2018, on 12 locations along the coast near the Klottey lagoon and Marine Drive project area. Two samples were taken just west and east of the mouth of the Klottey Lagoon (locations W0 and E0). The rest of the samples were taken every 500 m over a length of 2.5 km in both eastward and westward direction. The samples were taken on the beach approximately at the edge of the surf zone.

See figure 14.1 for an overview of the measuring locations.

Figure 14.1: Overview of the sediment sampling locations

The samples were transported in plastic bags. From every sample 150 g was taken and dried overnight in an oven. The next day the dry samples were loosened up and 100 g was separated. These 100 g samples were then sieved using a shaker table for 20 minutes. The available sieve sizes were 1.4 mm, 1.0 mm, 710 μm, 500 μm, 335 μm, 180 μm and 125 μm, leaving the leftovers in a bottom tray. The mass of these partitions was then measured with a scale and reported.

14.1.2. Results

The sieve curves for the 12 measuring locations can be seen in figure 14.2. A complete overview of the sieve tests can be found in appendix F.

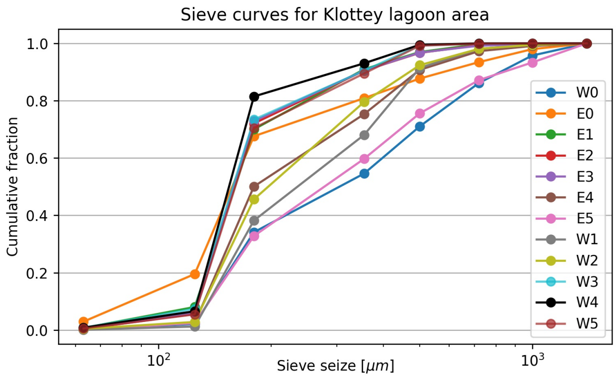


Figure 14.2: Sieve curves for the sediment samples

All but two locations show an approximate D_{50} of 150 μm. The locations with differing D_{50} are the one directly west of the lagoon mouth and the one furthest to the east. Here, the D_{50} doubles to around 300 μm. See table 14.1 for an overview of the median grain size per location.

Table 14.1: Median grain diameter per location

Location	W5	W4	W3	W2	W1	W0	E0	E1	E2	E3	E4	E5
D_{50} [μm]	161	154	158	196	235	305	157	160	159	159	180	278

14.1.3. Conclusion

The difference in median grain diameter can be explained by the fact that the dominant sediment transport is directed to the east. West of the Klottey lagoon, the Osu Castle (Christianborg Castle) blocks most of the sediment transport. Fine sediment can therefore be transported from just east of the castle, but new sediment from the west cannot reach it. That is why the sediment size increases. The same happens to the far east where rocks block the sediment transport.

14.2. Wave climate

Values for wave heights and directions are obtained from a wave hindcast model (Durrant et al., 2013). This dataset provides hourly significant wave heights, peak periods and wave directions from 1979-2010 based on recorded climate data. The average significant wave height for this location was H_s = 1.32 m. The average peak wave period was T_p = 9.27 s. The wave directions are very concentrated: 64 % of the waves come from southern direction and 36 % of the waves come from south-south-western direction. The average wave direction was 188.8°with a directional spreading of 22.8°.

In order to make an estimate of the longshore sediment transport, the wave height at breaking point needs to be calculated. The average wave angle and the average angle of the coast result in an average angle of incidence of 32 °. The breaker index was assumed to be γ = 0.78 (Bosboom and Stive, 2011). The wave height at breaking is iteratively calculated using the method in Bosboom and Stive (2011), resulting in the values provided in table 14.2.

Table 14.2: Values calculated from wave hindcast (Durrant et al., 2013) using methods and tables from Bosboom and Stive (2011)

Deep water wave height	L_0	134.2 m
Water depth at breaking	h_b	2.0 m
Shoaling coefficient	K_{sh}	1.31
Deep water wave celerity	c_0	14.5 m/s
Breaking wave celerity	c_b	4.37 m/s
Wave angle at breaking	ϕ_b	9.2 °
Breaking wave height	H_b	1.60 m

14.3. Sediment transport formulations

An estimate is made of the bulk sediment transport along the coast using various sediment transport formulations. After this, one of the transport formulations will be used to estimate the spatial variation of the sediment transport.

The transport formulations that are used in this section are valid for certain assumptions only and have their limitations. Therefore, the following results can be seen as crude estimates.

14.3.1. Bulk sediment transport

CERC First, the CERC (Coastal Engineering Research Center) formula is used. The formula, written in terms of wave height parameters, is shown in equation 14.1.

$$S = \frac{K}{16(s-1)(1-p)}\sqrt{\frac{g}{\gamma}}\sin{(2\varphi_b)}H_b^{2.5} \tag{14.1}$$

With:

S	=	sediment transport [m^3/s]
K	=	calibration coefficient [-]
p	=	porosity [-]
s	=	relative density sediment ($^{\rho_s}/_{\rho_w}$) [-]
g	=	gravitational acceleration [m/s^2]
γ	=	breaker index [-]
φ_b	=	angle of incidence of breaking waves [rad]
H_b	=	height of breaking waves [m]

The breaking wave height is 1.60 m, the angle of incidence of breaking waves is 9.2°and the breaker index is 0.78, as calculated in section 14.2. It is assumed that the sediment has a relative density of 2.65 and a porosity of 0.4.

The coefficient K is an empirical value that has to be calibrated for specific situations. It is dependent on whether the significant- (H_s) or root-mean-square wave height (H_{rms}) is used to calculate the wave height at breaking point. When H_{rms} is used, suggested values are K = 0.77 and K = 0.92. Because H_s is used in this case, these values should be converted such that $K_{H_s} \approx 0.4K_{H_{\mathrm{rms}}}$ (Bosboom and Stive, 2011).

Using these values, the yearly sediment transport volumes are calculated to be in the range of 2300$\times 10^3$ m^3/year to 2800$\times 10^3$ m^3/year, ranges 2 to 6 times higher than according to Giardino et al. (2017).

It is important to note that the CERC formula has its limitations. According to Smith, E. and Zhang, J. and Wang, P. (2003), sediment transport volumes are overestimated by a factor 3 to 8, because the formula is not sensitive to breaker type, which is an important factor in sediment transport. When K is calibrated using measured data, the error reduces to about 10 %. The Kamphuis (1991) formula is mentioned as a good alternative to the CERC formula, with errors ranging from 1 to 25 %. Similar findings are presented in van Rijn (2013), along with the proposal of a new calculation method. In the same report, the modified Kamphuis formula (Mil-Homens et al., 2013) proves to have smaller errors than the original.

In the following, the sediment transport will be calculated using the modified Kamphuis (Mil-Homens et al., 2013) formula and the Van Rijn formula (van Rijn, 2013).

Kamphuis The following method of Kamphuis (1991) includes the effects of grain sizes, beach slopes and wave steepness and is given by:

$$S = \frac{2.33 H_{s,b}^{2} T_p^{1.5} [\tan(\alpha_b)]^{0.75} D_{50}^{-0.25} [\sin(2\varphi_b)]^{0.6}}{\rho(s-1)(1-p)} \tag{14.2}$$

With:
α_b = The beach slope at breaker point [rad]
D_{50} = Grain size [m]
T_p = Peak period [s]
$H_{s,b}$ = Significant wave height at breaker point [m]

From measurements, it is found that the grain size D_{50} along a 5 km stretch around the mouth of the Klottey Lagoon are in the 150-350 μm range. Navigational charts of Navionics Inc. (2018) were used for bathymetric data of the coast. From these maps, the slope of the shore was estimated using the available 0-, 5- and 10 m depth contours. Because the data is quite coarse, the bottom slope at wave breaking cannot be accurately determined. The slopes are estimated to be between 1:100 and 1:10. As discussed in section 14.2 the peak period is equal to 9.27 s.

Using these values for equation 14.2 yields transport values in the range of 200 $\times 10^3$ m^3/year to 1600 $\times 10^3$ m^3/year. These values correspond better to the values found by Giardino et al. (2017) than the ones found using the CERC formula.

Van Rijn van Rijn (2013) proposes a transport formulation for the total longshore sediment transport, consisting of both suspended and bed load transport. In this formulation, the significant wave height and wave angle at the breakerline, the D_{50} and the slope of the beach material are the key influencing parameters.

The van Rijn (2013) formulation is defined by:

$$S = \frac{0.00018 K_{\text{swell}} \rho_s g^{0.5} (\tan\alpha_b)^{0.4} D_{50}^{-0.6} H_{s,b}^{3.1} \sin(2\varphi_b)}{\rho(s-1)(1-p)} \tag{14.3}$$

Because the percentage of swell is unknown for this coast, the assumption is that $K_{\text{swell}} = 1$. Using the values described above for equation 14.3 yields transport values in the range of 700 $\times 10^3$ m^3/year to 2000 $\times 10^3$ m^3/year. These results are similar to the ones obtained with Kamphuis' equation 14.2.

Discussion

The CERC formulation gives the highest values for the bulk sediment transport. However, the range between the values is smallest. This is because the CERC formulation does not take into account the slope of the beach front, which is an uncertain value, and to a lesser extent the grain size, which also varies a bit along the coast.

The Kamphuis and Van Rijn formulations give an estimate which is closer to the values described in Giardino et al. (2017). This is due to the fact that grain size and slope are included in the formulations. The spreading of these formulations is however larger than with the CERC formulation. This is because there is a lot of uncertainty in the beach slope at breaker point.

14.3.2. Spatial variation

In order to predict which coastal stretches are subject to erosion, the spatial variation of the sediment transport along the coast will be assessed. By looking at the difference in sediment transport between the different locations, a prediction of the erosion or accretion can be made.

A coastal area from approximately 5 km west to 5 km east of the Marine Drive project area is investigated. It is assumed that the wave climate and bed topography do not differ much over this coastal stretch. Therefore, a governing variable influencing sediment transport in this coastal stretch is the orientation of the coastline. To this end the coastline is cut up in stretches with approximately equal shoreline angles. See figure 14.3 for an overview.

Figure 14.3: Shoreline schematization

For practical reasons, a variation on the CERC formulation will be used to assess the spatial variation of the sediment transport. By assuming parallel depth contour lines, equation 14.1 can be rewritten in almost only deep-water wave characteristics. This makes the calculation most convenient. The quantity of sediment transport calculated using the CERC formulation was believed to be most inaccurate in the previous section. However, only a qualitative assessment on which locations will be subject to erosion or accretion will be done in this section. Therefore, this formulation will be used nonetheless. The formula is given in equation 14.4.

$$S = \frac{K}{32(s-1)(1-p)} c_b \sin(2\varphi_0) H_0^2 \tag{14.4}$$

In this formula, c_b is the only value that is defined at the breaker line. For the most accurate result, this value needs to be iteratively calculated for every shoreline angle. In this first estimate, an average wave celerity of c_b = 4.37 m/s is taken, as calculated in section 14.2.

From the calculated sediment transport values, the spatial variation dS/dx is determined. This provides an estimate on where to expect erosion and where to expect accretion. For each stretch, the sediment transport and the associated accretion or erosion is calculated. The results are presented in figure 14.4.

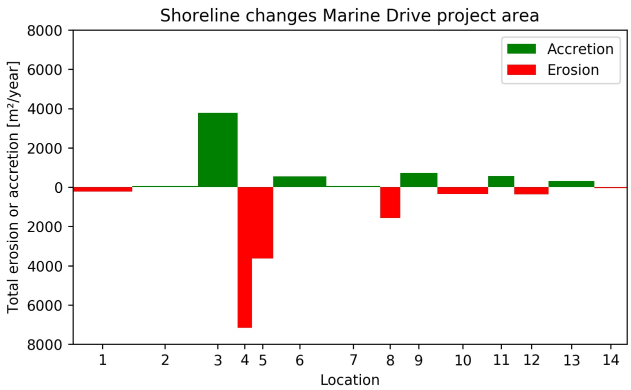


Figure 14.4: Accretion and erosion spots at the Marine Drive vicinity

It can be observed that there are locations in which there is heavy erosion or accretion. These are mainly at sharp corners in the coastline and are not entirely representative, since hard structures are not represented well in the CERC formulation. However, it is likely that just downstream of a sharp corner, heavy erosion or accretion takes place.

Looking at the locations near the Marine Drive and Klottey lagoon, it can be seen that these areas are quite stable. The Marine Drive beaches are even expected to accrete a little bit. Near the Klottey lagoon the Osu Castle causes sediment to be blocked resulting in some erosion east of the castle, next to the lagoon.

14.4. Future situation

After construction of the fishing harbour and the sea defence structure, there will be changes in sediment transport which may lead to accretion in some places and erosion in others.

The fishing harbour is expected to have a jetty east of the mouth of the Klottey lagoon extending several tens of metres into the sea. Depending on the kind of structure (open or closed) some sediment will be trapped by the jetty influencing the sediment transport along the coast. The single line theory of Pelnard-Considere (1956) (Bosboom and Stive, 2011) is an analytical solution which can be used to quickly assess the effects of a structure on the coast. Figure 14.5 shows what accretion near a breakwater looks like. On the other side of the breakwater, a mirrored erosion profile arises.

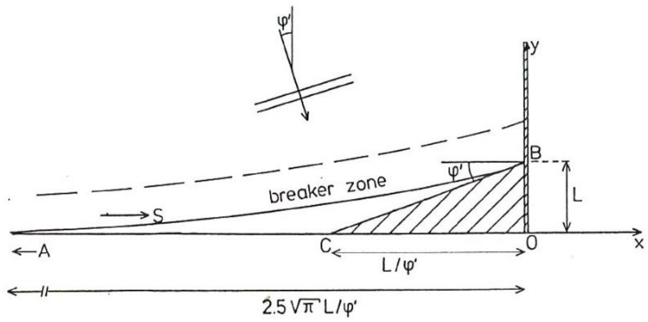


Figure 14.5: Accretion process near a breakwater

From the figure, it follows that the characteristic length over which a breakwater shows significant accretion or erosion is defined as $\frac{L}{\varphi'}$ and the effect is negligible at a distance of $2.5\sqrt{\pi}\frac{L}{\varphi'}$ with L given as:

$$L(t) = \varphi' \sqrt{\frac{4at}{\pi}} \tag{14.5}$$

With:

t	=	time [y]
φ'	=	angle of incidence [rad]
a	=	$\frac{S}{\varphi' d}$
d	=	profile height [m]
S	=	sediment transport [m^3/y]

Over a period of 5 years with an average sediment transport of 750 $\times 10^3$ m^3/y, an average breaking wave angle of 9.3°and a profile height of 10 m, this leads to a length of 1.7 km over which the accretion and erosion is significant. Given the fact that sediment transport is directed to the east and that the mouth of the Klottey lagoon is located only metres from the proposed jetty, sedimentation of the mouth of the lagoon poses a problem. The length after which the effects are negligible is 7.5 km. This means that downstream of the jetty, erosion of the coast is most likely to pose a problem. These effects have to be taken into account when designing the jetty.

For the Marine drive project site, a sea defence structure is planned. In what form this structure is to be built is unknown. If a groyne is planned, the same effects as with the jetty can be expected. This means that erosion and accretion can be expected at least a few kilometres before and after the groyne. If the sea defence structure is to be an detached breakwater, accretion can be expected behind the breakwater. Erosion is then expected just downdrift of the breakwater. See figure 14.6 for a schematic representation.

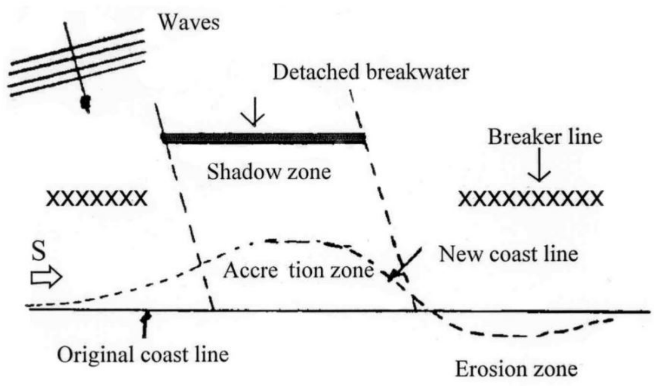


Figure 14.6: Accretion and erosion behind an detached breakwater

The construction of the sea defence structure will need to be analysed in detail. It may provide sheltering for swimmers and a wider beach at some locations, but it will cause erosion at other locations.

15
Conclusion and recommendations

15.1. Conclusion

The Klottey lagoon is a small lagoon with little to no outflow to the sea in dry weather conditions. During the dry season, it is likely that nutrients will flow into the lagoon from upstream and that the basin will reach high concentrations of pollutants.

Improving the area around the Klottey lagoon is possible. Improvements in sanitation are likely to be expensive and time consuming. A short term solution, which is cost effective and can be executed very fast, would be flushing. Another more expensive solution is a new structure between the sea and the lagoon. It is advised to integrate the re-design of the lagoon mouth and city drain at the same time. This redesign could make use of flushing the lagoon using tides, though minimal interaction between the sea and lagoon were observed.

15.2. Recommendations

Judging from the sand bar that is currently blocking the inflow of sea water into the lagoon, it is unlikely that a natural permanently open structure can be maintained without dredging the lagoon mouth on a regular basis. Fortunately, due to the small dimensions of the lagoon, this may be an achievable course of action.

Furthermore, the size of the lagoon allows for mechanical flushing with a stationary or even portable pump. As the lagoon has to serve as an attractive area for tourism, the waste on the banks should be taken away regularly and flushing of the lagoon is needed.

As for the effect of the polluted lagoon and city drain opening on the Marine Drive plans, the outlook is gloomy. The outflow of water from these sources is inevitable and at least some of the polluted water will flow along the Marine Drive. Therefore, effort should be made into tackling the source of the problem, being the cause of the bad water quality. Water treatment plants should be constructed and households should be connected to a sewage system. As for the solid waste in the water, campaigns may be helpful to decrease the amount of discarded garbage. Furthermore, a structured waste management system should be set up.

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A

Site visit to the Sakumo lagoon

This chapter summarises a site visit to the Sakumo lagoon on Tuesday the 13th of February 2018. It is intended to give a better view and understanding of what the mouth of the Sakumo lagoon looks like. Information gathered in communication with several stakeholders is added to this summary.

The visit took place between 11:50 and 12:20. High water was at 15:00 with a water level of 1.28 m relative to mean lower low water (MLLW). The water level during the visit was between 0.797 m and 0.878 m relative to MLLW, which is approximately at the mean sea level.

The lagoon mouth was the first stop of the site visit. The coastal stretch, including the lagoon mouth, was reconstructed in or just before 1953. A two-lane coastal road runs over an earthen embankment. The sea side is protected from wave attack by a riprap revetment. A rusty rail road track runs along the coastal road. Supposedly, a train ran over this rail road track twice daily, transporting workers to and from the port of Tema. However, the train had an accident three months ago, and is temporarily not running.

(a) Coastal road and rail road track

(b) Sea-side of the culvert

Figure A.1: View of the embankment separating the lagoon from the sea

The lagoon has two connections to the sea which lay in the embankment. The first structure is a concrete culvert which consists of two tubes with a diameter of 1.8 m that connect the lagoon to the sea directly. During the visit, water was flowing out of the lagoon via the culvert structure because the water at sea was lower than in the lagoon. With an occasional high wave at sea, water flowed into the lagoon via the culvert. From the lagoon to the sea, the tubes almost follow a straight line. The tubes are angled at the sea side, ending in openings directed to the east. This is to prevent sea water from hindering outflow of the lagoon after a heavy rainfall event. It is unclear whether the bottom of the culvert pipes are constructed horizontally or at an incline.

(a) Sea-side opening (b) Lagoon side opening

Figure A.2: Culvert openings

The culvert is in quite a bad state. There once was a sluice gate structure on the lagoon side to regulate the water exchange between the lagoon and the sea. These gates were closed in the dry season in order to retain a certain water level in the lagoon. The gates are now gone and few parts of the hoisting mechanism are recognisable. The year of construction, 1953, is engraved on the structure. On the seaside, the culvert has been damaged badly due to the salt water and wave attack. The top layer of the concrete has eroded almost everywhere on the sea side of the culvert. Cracks in the concrete can be seen in multiple places, and iron stains indicate corrosion of the reinforcement bars. On the sea side, the bottom part of one of the tubes of the culvert was eroded completely.

(a) Stream running towards the culvert (b) Storm drain (left) and culvert (right) on the lagoon side

Figure A.3: Overview of the mouth area of the lagoon

The other structure connecting the lagoon to the sea is a storm drain consisting of four tubes with a diameter of 1.4 m. It was constructed in 1997. During the visit, the tubes were at least one meter above the sea water level. Because of their elevation, these drains are only used after a heavy rainfall event when the capacity of the culvert is not enough to discharge the water from the lagoon. When the water level gets high enough, the water can flow out of the lagoon via the storm drain. The storm drain was clearly in a much better state than the culvert. Some cracks were present in the concrete, but the outer part of the concrete was not damaged due to wave attack or salt water.

The water quality in the lagoon seemed poor. Debris, mostly plastic, could be seen everywhere. The water smelled bad and next to the culvert on the lagoon side, the bed was covered with a white substance. Two streams joined together just before the culvert on the lagoon side. Water from one stream was black, while the other stream consisted of white water. A lot of debris was scattered throughout the riprap on the seaside of the revetment.

The site was visited during the dry season, during which water levels in the lagoon are low. The main basin was not visible, even from the elevated embankment. According to fishermen, there is still water in the lagoon. However, invasive plant species have overgrown the entire lagoon in recent years, making it impossible to see the main water body.

(a) Lagoon side opening

(b) Sea side opening

Figure A.4: Storm drain openings

The site visit confirms the bad state the lagoon is currently in. Water quality seemed very poor and fishing is not possible any more due to the invasive plant species.

B

Site visit to the Klottey Lagoon and Marine Drive project area

This appendix describes the site visit to the Klottey Lagoon and Marine Drive project area on Saturday 10 February 2018. The start of the visit was at 9:40 and it ended around 10:30.

B.1. Klottey Lagoon

Three big pipes are constructed at the upstream end of the lagoon, serving as a storm drain for the area. A lot of litter was floating in the water, mainly water bottles. The water itself looked green, with oil marks and pink foam floating on top. The site had an unpleasant smell. It could not be determined if the smell came from the water or from waste on the banks. A lot of garbage was laying on the banks, including plastic bottles and clothes.

(a) The storm drain

(b) View on the basin, looking toward the southeast

Figure B.1: View on the upstream end of the lagoon

At the downstream end of the lagoon, plastic debris was floating on the water. The amount of litter was far less than at the upstream end. At the mouth, there is a concrete structure that connects the lagoon to the sea. On top of the bottom slab of this structure, sand has accumulated that closes off the lagoon. Although it was almost high water during the site visit, there was no interaction between the sea and the lagoon.

The structure is in bad condition. Large parts of the structure have eroded. Some traces of a more complex system are visible. In the structure, there are signs of a gate or sluice system that has once been constructed. These grooves are now used for an improvised pedestrian bridge over the structure.

Next to the lagoon mouth, a city drainage channel discharges into the sea. The water of this drainage channel is of black colour and smells very bad. The mouth of the channel was filled with sediment. The water has made a path toward the sea through the layer of sand. The mouth of the city drain also has a discharge structure at the sea side. This structure inhibits the water of the drainage channel from flowing into the lagoon.

(a) The city drain

(b) Mouth of the Klottey lagoon

Figure B.2: View of the downstream end, looking toward the north

About 20 fishing boats were berthed on the beach at the east of the lagoon. These boats were lying on the higher part of the beach. The beach is quite steep. From this, we assume that a part of the beach has already eroded. On the higher parts of the beach, a fishing boat was being constructed. To the east of the collection of fishing boats, there seemed to be a hangout for the local people.

B.2. Marine Drive Project site

The Marine Drive Project Site is located to the west of the lagoon. It spans a beachfront of 2.5 km. The Independence Square is situated in the middle of the project site. Hotels and other touristic attractions will be constructed around this square. The project site is a plane building site. It is unsure if the whole building site is ready for construction of the hotels. From a distance, some excavators and trucks working to move land and make the site ready for construction could be seen.

About five drainage streams were seen running over the beach into the sea. The most westward one was most clearly a city drain channel. The others were small streams running over the beaches to the sea. Two of the streams had concrete gutters laying nearby. These gutters are probably old drainage systems, which have broken down over time.

Various types of litter were present across the beach. Most of the litter was piled up in heaps on the beach. The piles originate from fishermen emptying their nets on the beach, because these nets contain a lot of waste. The amount of garbage in the nets of the fishermen was more than twice the amount of fish.

Along the whole stretch, a few simply constructed houses were located. These houses are most likely not connected to a sewage system, which means that the beach is also polluted with the urine and faeces of the people living on the beach.

(a) View on the construction site

(b) A drainage channel running across the beach

Figure B.3: View of the Marine Drive beach front

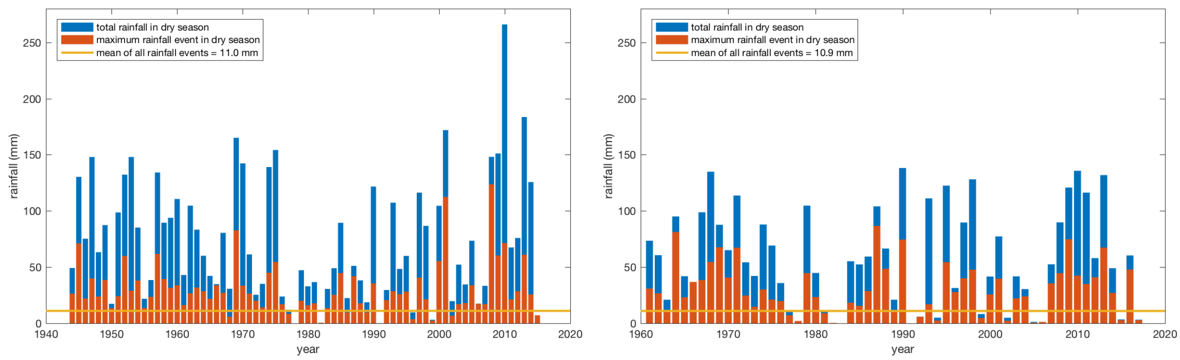
C

Rainfall data analysis

C.1. Normal conditions

The Greater Accra Region experiences a main wet season, a minor wet season and a dry season. The normal conditions will be split up into the main wet season and the main dry season.

First, the dry season condition will be estimated through taking the mean rainfall event in the dry season. The dry season ranges from halfway November to the end of February. The total rainfall along with the maximum one-day value for the dry seasons in both Accra and Tema are shown in figure C.1. The mean rainfall event in the dry season amounts to 11 mm in both Accra and Tema. The average total rainfall during the dry season is 74 mm in Accra and 58 mm in Tema.

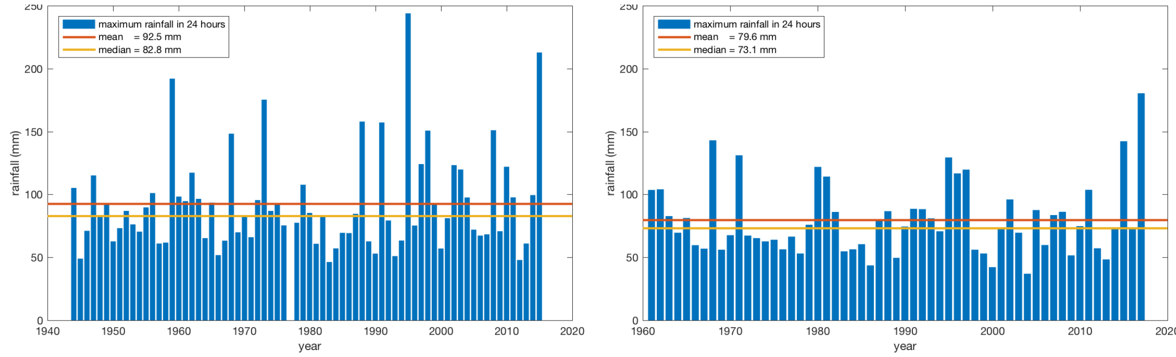


(a) Accra

(b) Tema

Figure C.1: Rainfall in the dry season

Second, the normal wet season conditions are estimated. For Accra, the maximum 24-hour rainfall event is determined for each year in the period of 1944 to 2015. For Tema, the period of 1961 to 2017 is used. From these yearly maxima, the mean and median values are calculated. This is shown in figure C.2. The median values in Accra and Tema measure 83 and 73 mm, respectively, and will serve as measures for a normal wet-season rainfall event.

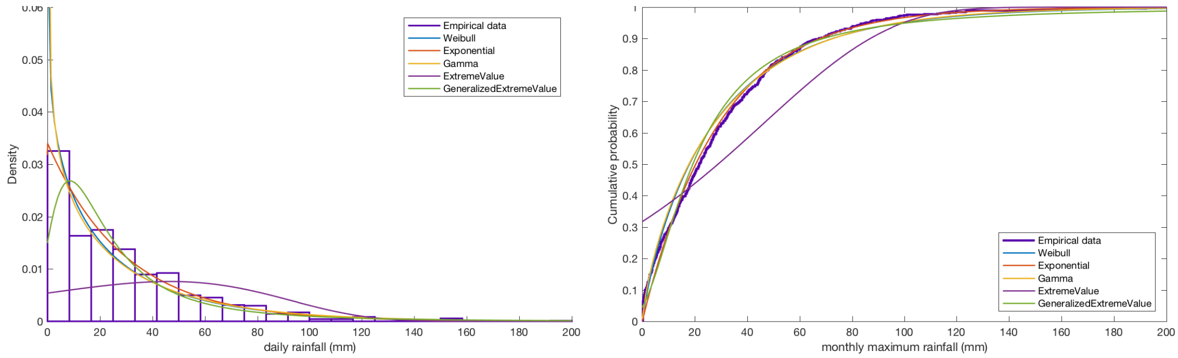


(a) Accra (b) Tema

Figure C.2: Yearly maximum rainfall events

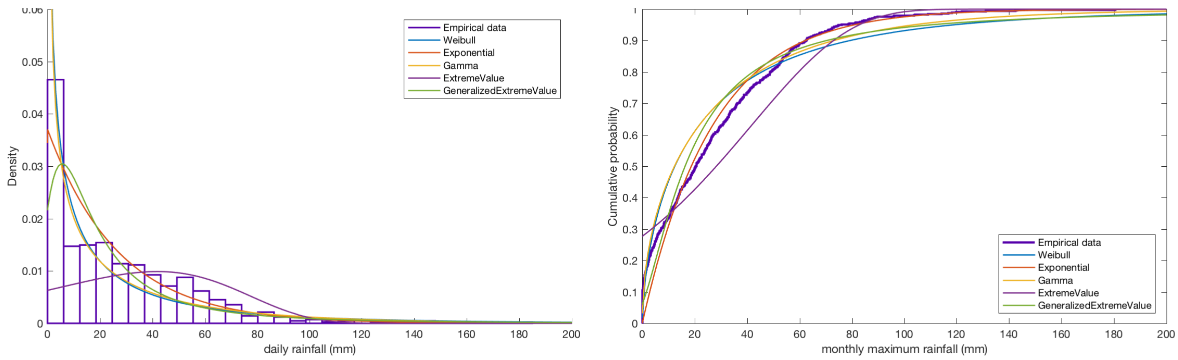
C.2. Extreme conditions

In order to obtain extreme rainfall values, the monthly maxima were extracted from the datasets and a probabilistic distribution was fitted upon these data. The result for Accra can be seen in figure C.3 and for Tema in figure C.4.



(a) Probability distribution function (b) Cumulative distribution function

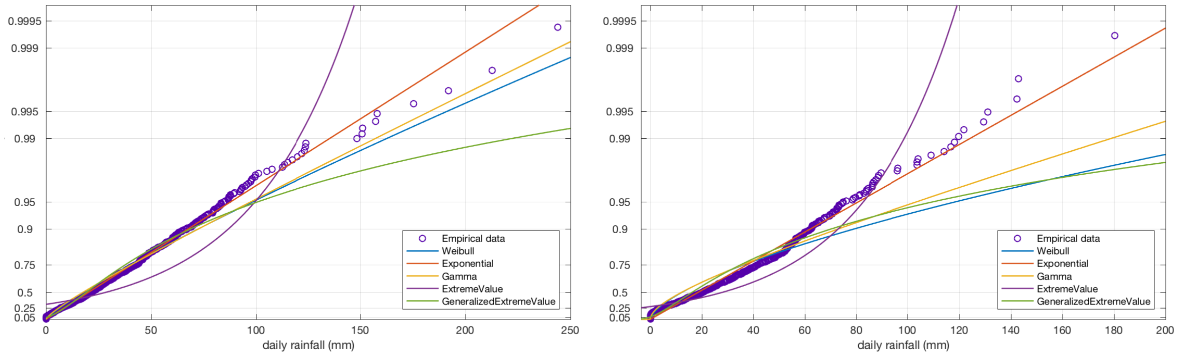
Figure C.3: Distribution fitting of monthly maximum rainfall at Accra Airport synoptic station



(a) Probability distribution function (b) Cumulative distribution function

Figure C.4: Distribution fitting of monthly maximum rainfall at Tema synoptic station

In the lower rainfall values, either the exponential or Weibull distribution seem to be the best fit. In the tail, all distributions but the extreme value distribution seem to fit well. Because the extreme values are most interesting, the tail is further examined by means of a probability plot shown in figure C.5.



(a) Accra (b) Tema

Figure C.5: Probability plots at Accra and Tema

The Weibull, Exponential and Gamma distributions seem to represent the tail of the Accra dataset quite well. However, the Weibull and Gamma distributions overestimate the severity of the rainfall events in Tema. Assuming that the Accra and Tema rainfall dataset are drawn from the same distribution, the exponential distribution is chosen to be the most accurate for predicting the return period of certain rainfall events.

Rainfall events are calculated for several return periods using the fitted exponential distribution. The results, including the comparison with Tema, are shown in figure C.6

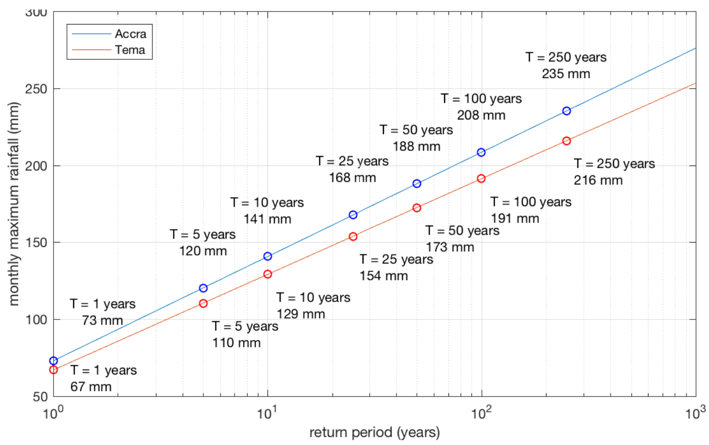


Figure C.6: Several return periods of monthly maximum rainfall events for the Accra and Tema measuring stations

The design return period is determined using the Poisson approximation, given in equation C.1.

$$P = 1 - \exp(-fT) \tag{C.1}$$

The Poisson approximation is used to calculate the probability of failure in a certain time period, caused by an event with a certain return period. Assuming a lifetime of $T = 50$ years, the design return periods for $P_{\text{failure}} = 1\%, 5\%$ and 10% are calculated. Using these design return periods, the corresponding rainfall event is determined using the fitted probabilistic distribution. The results are given in table C.1.

Table C.1: Extreme rainfall events based on probability of failure in a lifetime of 50 years

P_f	1%	5%	10%
Corresponding return period (years)	4975	975	475
Rainfall Accra (mm)	323	275	254
Rainfall Tema (mm)	297	253	233

D

Hydrological model

A representative hydrological scenario is set up in the way used by HKV for the Odaw basin. The set up is summarized below.

1. A meteorological event is designed using the alternating block method with one hour blocks (Chow et al., 1988) based upon the IDF curve provided by GMET. This is done using either a design period or a known precipitation amount.

2. As a larger area has on average a lower precipitation intensity, an Area Reduction Factor (ARF) has to be used. Since there is no general formula for this ARF, an equation was set up by HKV which is based upon TRMM data and point measurements at airport synoptic station provided to them by GMET.

$$ARF = \frac{P_A}{P_P} = 0.45e^{-\frac{A}{350}} + 0.55 \quad \text{(D.1)}$$

   with: P_A = Average area precipitation P_P = point measured precipitation A = surface area with PA = average area precipitation, PP = point measured precipitation and A = surface area.

3. Correct for interception storage;

4. Apply Horton equation for infiltration;

5. Subtract 1.5-10 mm of the first block as surface storage, depending on coverage.

Using this method, a 24-hour design event is set up. This design event can then be used as input for the hydraulic model so that the routing of the water can be calculated.

E

Water quality analysis

Figure E.1: Measurement locations at the mouth of the Sakumo lagoon

Table E.1: Results of nutrient analysis of the Sakumo lagoon

Measurement		PO4 Phosphorous [mg/l]	NH3-N Ammonia [mg/l]	NO3-N Nitrate [mg/l]
LW	1	7.40	32.76	2.30
	2	7.70	26.31	2.20
	3	7.20	21.39	2.60
	μ	7.43	26.82	2.37
	σ	0.25	5.70	0.21
HW	1	0.11	0.10	0.70
	2	0.08	0.06	0.80
	3	0.05	0.05	0.30
	μ	0.08	0.07	0.60
	σ	0.03	0.03	0.26
	4	1.30	1.72	2.00

Table E.2: Results of probe measurements at Sakumo lagoon

		Temperature	Acidity		Redox potential	Turbidity	Dissolved Oxygen		Total Dissolved Solids	Conductivity	Salinity	Density
		T	pH	pHmV	ORPmV		DO	DO	TDS			σ_T
Measurement		[°C]	[-]	[mV]	[mV]	[NTU]	[mg/l]	[%]	[g/l]	[mS/cm]	[ppt]	[ρ-1000 kg/m^3]
LW	1	29.13	6.42	-35.00	-159.00	42.30	0.43	5.70	2.05	3.20	1.70	0.00
	2	28.19	5.98	-9.00	-141.00	38.80	0.36	4.70	1.52	2.30	1.20	0.00
	3	29.42	5.88	-2.00	-135.00	63.10	0.35	4.60	1.89	2.84	1.50	0.00
	μ	28.91	6.09	-15.33	-145.00	48.07	0.38	5.00	1.82	2.78	1.47	0.00
	σ	0.64	0.29	17.39	12.49	13.14	0.04	0.61	0.27	0.45	0.25	0.00
HW	1	29.64	8.17	-140.00	31.00	33.20	6.26	102.80	32.70	54.60	36.10	22.90
	2	29.36	8.07	-134.00	77.00	37.10	6.12	93.10	31.70	51.10	33.00	20.60
	3	29.44	8.18	-140.00	53.00	33.40	6.10	99.90	32.78	54.60	36.10	22.90
	μ	29.48	8.14	-138.00	53.67	34.57	6.16	98.60	32.39	53.43	35.07	22.13
	σ	0.14	0.06	3.46	23.01	2.20	0.09	4.98	0.60	2.02	1.79	1.33
	4	33.03	7.68	-111.00	-10.00	90.40	6.51	94.00	9.76	15.10	8.60	1.30

Figure E.2: Water quality and sediment sampling locations in and near the Klottey Lagoon

Table E.3: Results of measurements at Klottey lagoon

Measurement		PO4 Phosphorous [mg/l]	NH3-N Ammonia [mg/l]	NO3-N Nitrate [mg/l]	Salinity [PSU]	Temperature [°C]
Klottey	K1	1.28	3.74	40.80	3.21	34.44
	K2	2.13	2.95	9.80	4.24	34.87
	K3	4.50	3.30	7.00	10.17	33.11
	K4	4.79	2.49	11.80	15.98	31.42
City drain	CD	20.07	38.01	36.60	0.35	37.49
Sea	W0	0.11	0.09	1.30	43.83	30.79
	E0	0.16	0.41	1.40	44.07	30.85
	W5	0.13	0.09	0.90	-	-
	E5	0.15	0.17	0.60	-	-

F

Sediment analysis

In order to say something about the coastal erosion along the Klottey and Marine Drive beaches, sediment samples were collected. Samples were taken every 500 m along a 5 km stretch of coast. Each sample location was numbered, starting from the Klottey lagoon, ascending in eastern and western directions (E0-E5 and W0-W5 respectively, see figure F.1). These sediment samples were dried overnight in an oven. A portion of 100 g of every sample was then sieved using various available sieve sizes (see table F.1). After the sieving all partitions were weighed. The masses of these partitions can be found in table F.1. These measurements result in the sieve curves in figure F.2.

Figure F.1: Overview of the sediment sampling locations

Table F.1: Mass [g] per sieve size for every measurement location

	Location											
Sieve size	W5	W4	W3	W2	W1	W0	E0	E1	E2	E3	E4	E5
1400 μm	0.0	0.0	0.0	0.5	0.5	4.2	2.0	0.1	0.2	0.3	0.9	6.6
1000 μm	0.1	0.0	0.1	1.4	1.4	9.5	4.5	0.2	0.4	0.5	1.8	6.1
720 μm	0.7	0.5	0.6	5.7	6.6	15.0	5.7	2.7	2.7	2.4	6.5	11.5
500 μm	9.6	6.4	8.8	12.8	23.1	16.3	6.8	6.0	6.2	6.2	15.4	15.7
355 μm	18.9	11.5	17	33.9	29.6	20.3	13.2	20.9	18.4	17.6	25.2	26.7
180 μm	64.4	74.4	65.8	42.7	36.6	31.7	47.8	61.8	66.4	66.7	47.5	30.1
125 μm	4.9	5.7	6.6	2.4	1.1	2.0	16.5	7.3	5.2	5.1	2.1	2.3
Residual	0.5	0.8	0.8	0.4	0.1	0.1	2.9	0.7	0.4	0.7	0.3	0.1
Total	**99.1**	**99.3**	**99.7**	**99.8**	**99.0**	**99.1**	**99.4**	**99.7**	**99.9**	**99.5**	**99.7**	**99.1**

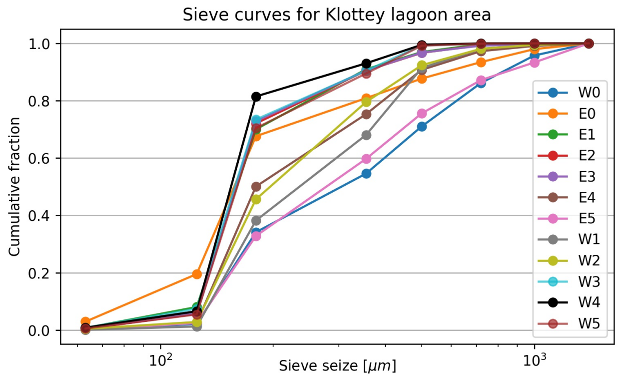


Figure F.2: Sieve curves for the sediment samples