Rehabilitation of the former Northern Swamp Lake Naivasha – Kenya

On the modeling of the sediment trapping efficacy for two rehabilitation alternatives

M.A.J.M. Cornelissen BSc

UNIVERSITY OF TWENTE.

ITC Faculty of Geo-Information Science and Earth Observation

Rehabilitation of the former Northern Swamp Lake Naivasha – Kenya

On the modeling of the sediment trapping efficacy for two rehabilitation alternatives

Master thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Civil Engineering and Management

At the

University of Twente

By

M.A.J.M. Cornelissen BSc

Civil Engineering (University of Twente)

d.d.

March 28, 2014

Under supervision of

Dr. ir. D.C.M. Augustijn

University of Twente, Department of Water Engineering and Management

Dr. ir. P.R. van Oel

University of Twente, Department of Urban and Regional Planning and Geo-information Management

With the support of the Kenyan

WATER RESOURCES MANAGEMENT AUTHORITY (WRMA)

SUMMARY

Erosion, induced by natural processes such as wind and rainfall and enhanced by anthropogenic activities such as agribusiness and deforestation, produces sediments that are carried downstream by rivers. The deposition of the sediments in the downstream areas creates new landmass for various life forms to live. However, the downstream deposition also causes problems such as sediment accumulation in delta regions and near boat ramps hindering navigation, and altering of the species composition affecting the ecological state. Erosion and the related problems also occur in the Lake Naivasha Basin, which is situated 80 km northwest of Nairobi in Kenya. The siltation affects the turbidity of the water with indirect influences on water use for human activities, fisheries, tourism and agriculture such as the flower business. The higher erosion rates which cause increasing sedimentation of the lake also cause greater inputs of nutrients and pollutants to the lake. These nutrients and pollutants threaten the ecological state of the lake, i.e. by an increased nutrient concentration.

A possible solution to decrease the siltation of the lake is to rehabilitate the former Northern Swamp, a former wetland of about 4 km² north of Lake Naivasha to retain sediments and prevent them from ending up in the lake. In 2009, Marula Estates, a large commercialized agricultural landholding bordering the former Northern Swamp, on its own initiative performed a study on the current state of the wetland and created a plan to rehabilitate the former Northern Swamp. The first phase of this plan was implemented already in 2009 and because the results are satisfying, the second phase of the project, which consists of the construction of a dam to buffer water from the Malewa River, will be implemented. The implementation of the second phase however is currently on hold due to the high lake water level, which needs to drop sufficiently to provide access for machinery to execute the necessary works. This forced break gives the opportunity to review the design from a Water Engineering perspective, which led to the research objective of this study: "*To evaluate the functioning of two alternative rehabilitation alternatives, with in particular the sediment trapping efficacy, by modeling the sediment transport processes for various Malewa River discharges using a one-dimensional modeling approach*". The first rehabilitation alternative is a wetland through which the water flows from the Malewa River via a spillway channel and wetland into Lake Naivasha, based on the design as presented by Marula Estates (2013). The second alternative consists of the same spillway channel to divert the water from the Malewa River into a meandering channel flowing into Lake Naivasha.

To achieve this research objective, a literature study and field work, in May – June 2013, are done to get insight in the former Northern Swamp and the rehabilitation plan. To model the sediment transport processes an empirical formula that relates sediment load and discharge is used together with an integrated software package for river management called SOBEK. With this model it is possible to make an estimation of the amounts of sediments entering through the inlet construction, and it is possible to get insight in the sediment transport processes within the two rehabilitation alternatives.

The Wetland alternative turns out to be the best alternative when considering sediment trapping efficacy. For the year 2010, when taking into account the maximum discharge entering the wetland of 25 m³/s to prevent flooding of the spillway channel, the sediment inflow into Lake Naivasha could have been reduced with 15%. Due to the current wetland design specifications, based on discharge data from 1960 till 2010, on average only 1.25% of the time water can be diverted from the Malewa River through the spillway channel into the wetland. For 2010 however, water could have been diverted for almost 7% of the time and therefore, the reduction in sediment inflow into Lake Naivasha is likely to be lower for other years. Also, due to the limited possibility of utilization of the wetland, rehabilitation of the former Northern Swamp is going to be difficult.

SAMENVATTING (IN DUTCH)

Erosie, veroorzaakt door natuurlijke processen zoals wind en neerslag en versterkt door antropogene processen zoals landbouw en ontbossing, leidt tot de vorming van sedimenten die door rivieren naar benedenstrooms worden getransporteerd. Het neergeslagen sediment in benendenstroomse gebieden creëert een nieuwe leefomgeving voor verschillende levensvormen. Echter, het neerslaan van sediment in benedenstroomse gebieden veroorzaakt problemen zoals ophoping van sediment in deltagebieden en in de buurt van steigers wat hinder oplevert voor de scheepvaart en veroorzaakt verandering in de samenstelling van plant- en diersoorten wat weer invloed heeft op de ecologische staat van deze gebieden. Erosie en de daaraan gerelateerde problemen komen ook voor in het Lake Naivasha stroomgebied, 80 km ten noordwesten van Nairobi in Kenia. De aanslibbing heeft invloed op de troebelheid van het water, wat weer direct invloed heeft op het watergebruik voor menselijke activiteiten, de visserij, toerisme en de landbouw zoals de bloemenindustrie. De hogere mate van erosie heeft toenemende aanslibbing in het meer en toenemende toestroom van nutriënten en verontreinigingen als gevolg. Deze nutriënten en verontreinigen bedreigen de ecologische staat van het meer, bijvoorbeeld door een verhoogde nutriënt concentratie.

Een mogelijke oplossing om de aanslibbing van het meer te verminderen is het rehabiliteren van het voormalige Northern Swamp, een voormalig wetland van ongeveer 4 km² ten noorden van Lake Naivasha. In 2009 heeft Marula Estates, een grote commerciële boerderij grenzend aan het voormalige Northern Swamp, op eigen initiatief een studie uitgevoerd naar de huidige staat van het voormalige Northern Swamp en een plan ontwikkeld om het gebied te rehabiliteren. De eerste fase van het plan is geïmplementeerd in 2009 en omdat de resultaten daarvan bevredigend waren is besloten om de tweede fase van het project, dat bestaat uit het opwerpen van een dam om het water uit de Malewa River op te stuwen, ook uit te voeren. De uitvoering van de tweede fase is echter momenteel stilgelegd omdat de hoge waterstanden in het meer eerst moeten dalen zodat het gebied toegankelijk wordt voor het materieel om de nodige werkzaamheden uit te voeren. Deze verplichte onderbreking biedt de mogelijkheid om het ontwerp door te lichten vanuit een waterbouwkundig perspectief wat heeft geleid tot het doel van deze studie: *"Het evalueren van het functioneren van twee rehabilitatie alternatieven, met in het bijzonder de sedimentafvangcapaciteit, door het modelleren van de sediment transportprocessen voor variërende Malewa afvoeren met behulp van een een-dimensionaal model"*. Het eerste alternatief is een wetland waardoor het water vanuit de Malewa Rivier en via een omleidingskanaal naar het meer stroomt, wat is gebaseerd op het ontwerp zoals dat is gepresenteerd door Marula Estates (2013). Het tweede alternatief bestaat uit hetzelfde omleidingskanaal om het water vanuit de Malewa Rivier af te leiden naar een meandered kanaal dat uitmondt in Lake Naivasha.

Om deze doelstelling te bereiken is een literatuurstudie en veldwerk, in de periode van mei – juni 2013, uitgevoerd om zo inzicht te krijgen in het voormalig Northern Swamp en het rehabilitatie plan. Om de sediment transport processen te modelleren, is een empirische formule gebruikt die de relatie tussen de sediment concentratie en afvoer beschrijft samen met een software pakket voor rivierbeheer genaamd SOBEK. Met dit model is het mogelijk om een schatting te maken van de hoeveelheid sediment die het systeem instroomt door het inlaatwerk, en is het mogelijk om de sediment transport processen te beschrijven in de twee alternatieven.

Het Wetland alternatief lijkt het meest geschikt wanneer de nadruk ligt op de sediment afvangcapaciteit. In het jaar 2010, wanneer een maximale afvoer die het wetland instroomt van 25 m^3/s wordt aangenomen om zo overstroming van het omleidingskanaal te voorkomen, zou de instroom van sediment naar Lake Naivhasha met 15% verminderd kunnen zijn. Door de ontwerp specificaties, gebaseerd op afvoer data van 1960 tot 2010, kan er gemiddeld maar 1.25% van de tijd water worden afgeleid vanuit de Malewa door het omleidingskanaal naar het wetland. Echter in 2010, kon er 7% van de tijd water worden afgeleid en het is daarom aannemelijk dat de afname in sedimenttoevoer naar Lake Naivasha lager is voor andere jaren. Ook is het lastig om het voormalige Northern Swamp te rehabiliteren doordat het wetland maar beperkt kan worden ingezet.

PREFACE

In this Master Thesis, the results are presented of the research I conducted in the past year in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering & Management, with the focus on Water Engineering & Management. The objective of this research was to get insight in the impacts of the rehabilitation of a former swamp north of Lake Naivasha in Kenya, using a simple one-dimensional hydrodynamics model in an integrated software package for river management.

The research was conducted This research is part of the project 'An Earth Observation- and Integrated Assessment (EOIA) approach to the governance of the Lake Naivasha basin in Kenya' executed by the ITC, the Faculty of Geo-Information Science and Earth Observation of the University of Twente. I would like to thank Denie Augustijn, my UT supervisor, and Pieter van Oel, my daily supervisor, which provided with me useful feedback that helped me to improve my research. I enjoyed my time at the ITC office in the Naivasha-room among my Dutch, Kenyan and Ethiopian colleagues, during which they were always willing to exchange thoughts about my research. Therefore I would like to thank Dawit Mulatu, Francis Muthoni, Frank Meins, Jane Ndungu, Job Ogada, Rick Hogeboom and Vincent Odongo. From May 18 till June 14, 2013, I went to Kenya where I was warmly welcomed by Francis his cousin, John Kamau. The purpose of this visit was to execute field work, with which I was greatly supported by the WRMA employees for which I would like to thank them. My special thanks go out to Dominic Wambua for helping me to arrange the field work, and Marula Estates for their hospitality. In the weekends, exploring the area together with Frank led to memorable adventures.

By completing this Master Thesis, not only this research comes to an end, but also my time as a student here at the University of Twente in Enschede. I would like to thank my friends for all the great times we had, already from the moment we met in the summer of 2007. Finally I would like to thank my parents Jan and Gonnie, who made it possible for me to achieve all this by their wholehearted support and encouragement.

Mark Cornelissen

Enschede, March 2014

CONTENTS

Chapter 1 – Introduction

This chapter serves as an introduction on this research and the case, and starts with general background information about the processes of erosion and sedimentation, the problems caused by sedimentation and two possible measures to mitigate these problems. These processes are then explained for the Lake Naivasha Basin in particular, together with the Wetland rehabilitation project initiated by Marula Estates. These processes and the related problems are then formed into a problem statement, based on which the research objective and questions are developed. This chapter concludes with the outline of this thesis.

1.1 Background

Exogenous processes on the rocks that form the earth's crust, such as wind, rainfall, temperature, glaciers and vegetation lead to weathering, loosening, diminishing and transporting of soil particles called sediments. These processes, also called erosion, cause the earth's relief to be changed, since the sediments are being transported through water, ice and wind under the action of gravity from high altitude regions such as mountains to low altitude regions such as lakes and seas. In addition to the above described natural exogenous processes, anthropogenic activities such as agribusiness and deforestation give rise to erosion (WorldRiskReport, 2012). Erosion itself causes problems in the upstream areas of a basin, but also the deposition of the sediments in the downstream areas causes problems such as sediment accumulation in delta regions and near boat ramps hindering navigation, and altering of the species composition affecting the ecological state (Morris et al., 1998). Wetlands, defined as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" by Ramsar (1971), can serve as a possible solution to reduce the downstream transport of sediments and therefore the siltation of lakes and reservoirs, since they are effective sediment traps meaning that they generally intercept and retain more sediments than they export. Overall, measured values reported in the literature indicate that sediment removal efficiencies range between 80-90% (Daukus et al., (1989) as cited in Siobhan Fennessy et al. (1994)). However, sediment deposition in lakes, but also in wetland ecosystems, is one the most difficult parameters to measure (Siobhan Fennessy et al., 1994).

1.2 Lake Naivasha

The processes described above and the related problems also occur in the Lake Naivasha Basin, situated 80 km northwest of Nairobi in Kenya. A possible solution to decrease the siltation of the lake is also there in the form of rehabilitating the former Northern Swamp, a former wetland of about 4 km² north of Lake Naivasha (Marula Estates, 2009). Lake Naivasha is a tropical freshwater Ramsar site and the fact that it is acknowledged as such by the Ramsar Convention, The Convention of Wetlands of International Importance, reveals already its value. To also protect the coherent sites, wetlands, as defined by Ramsar (1971), "may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands". The natural resource system, including Lake Naivasha and the riparian zone with its water, flora and fauna, serves several functions. Its freshwater supports a rich ecosystem, with hundreds of bird species, papyrus fringes occupied by hippos, riparian grass lands grazed by waterbucks, giraffes, zebras and various antelopes, dense patches of riparian acacia forest with buffaloes and bushbucks, and swampy areas where waterfowl breed and feed (Becht et al., 2005). Next to its ecological function, the lake and its water is used for irrigation, electricity generation, fish cultivation, drinking water and recreation and tourism (Lukman, 2003).

To ensure a sustainable use of the resources that Lake Naivasha has to offer, good understanding of the processes that take place in and around the lake is essential. To gain this understanding, a project named 'An Earth Observation- and Integrated Assessment (EOIA) approach to the governance of the Lake Naivasha basin in Kenya' is being executed by the ITC, the Faculty of Geo-Information Science and Earth Observation of the

University of Twente. Within this project, five subprojects are being executed focused on hydrology, limnology, fringe ecology, socioeconomics and water governance. This study is a part of the EOIA project and contributes to the improvement of the understanding of the processes concerning the inflow of sediments and the possibilities to reduce this inflow by rehabilitating the former Northern Swamp. An important EOIA project partner is the Water Resources Management Authority (WRMA), with its mission “to regulate and manage water resources use effectively involving stakeholders for sustainable development” (WRMA, 2013).

In 2009, Marula Estates, a large commercialized agricultural landholding bordering the former Northern Swamp, on its own initiative performed a study on the current state of the wetland and created a plan to rehabilitate the former Northern Swamp (Marula Estates, 2009). The first phase of this plan, which consisted of the construction of a dam in the Gilgil River, was implemented already in 2009 and because the results are satisfying, the second phase of the project, which consists of the construction of a dam to buffer water from the Malewa River, will be implemented (Marula Estates, 2013). The implementation of the second phase however is currently on hold due to the high lake water level, which needs to drop sufficiently to provide access for machinery to execute the necessary works. This forced break gives the opportunity to review the design from a Water Engineering perspective in order to evaluate the sediment trapping efficacy of two rehabilitation alternatives.

The focus of this study is, similar to the Marula Estates initiative, on the rehabilitation of the former Northern Swamp, in which a wetland will be created, that will be fed by the Malewa River. The reason to focus on this measure is because of the Marula Estates initiative, but also other reasons are there to support this focus. Harper et al. (1999) propose this measure as a primary, most feasible and cost efficient tool for the restoration of Lake Naivasha by reducing the inflow of nutrients, organic and mineral matter provided by the Malewa River. The main part of the annual sediment load is transported by fluxes during heavy rains. Since the Malewa River contributes for 80% to the total inflow to the lake (Becht et al., 2005), this measure designed for the Malewa River seems promising to mitigate the inflow of sediments and nutrients into the lake. Also according to scientific literature a wetland seems to be a promising measure, it is estimated that sedimentation processes and biogeochemical trapping in the sequential treatment wetland should reduce the inflow of suspended matter and phosphorus up to 80% and over 50% respectively. Downstream measures, such as the construction of a wetland in the Malewa River (Harper et al., 1999) and the construction of a barrier in the Gilgil River (Githaiga (2008) as cited in Morrison et al. (2009)) are also proposed by Morrison et al. (2009). Also Siobhan Fennessy et al. (1994) state that downstream wetlands have a more substantial effect on the water quality compared to upstream wetlands, meaning that the sediment retention is higher. Taking into account these arguments it can be stated that a downstream measure in the Malewa River, such as the rehabilitation of the former Northern Swamp by constructing a wetland fed by the Malewa River, seems to be promising, however the impacts are not quantified yet. The increased sedimentation rate in Lake Naivasha however is quantified, and will be discussed in the next section.

1.3 PROBLEM STATEMENT

The main sources of sediment flowing into the lake are the Malewa and Gilgil River upper catchments, where due to land use changes the sediment load certainly has increased (Becht et al., 2005). The increase in sediment load is also described by Harper et al. (2004) and Everard et al. (2002) who state that this increase is caused by the proliferation of small-scale agriculture in the wider basin that has led to cultivation on river banks. It is estimated by Rupasingha (2002), that siltation of Lake Naivasha takes place with a rate of 0.5 cm per year, based on data from the period 1957-2001. A more recent study on the sedimentation of the lake was executed by Stoof-Leichsenring et al. (2011) who determined the sedimentation rate based on a sediment core sample taken in 2007. According to this study, in the late nineties the sedimentation rate was approximately 0.5 cm per year, but this rate has increased up to over 1 cm per year in 2006.

Many landowners consider soil erosion in the Lake Naivasha basin as a problem (Willy et al., 2012), together with the siltation of the lake (Becht et al., 2005). The siltation affects the turbidity of the water with indirect influences on water use of human activities, fisheries, tourism and agriculture such as the flower business (Willy et al., 2012). The higher erosion rates which cause increasing sedimentation of the lake also cause greater inputs of nutrients and pollutants to the lake (Rupasingha, 2002). These nutrients and pollutants threaten the ecological state of the lake (Kitaka et al., 2002), for example by eutrophication of the lake (Stoof-Leichsenring et al. (2011), Ndungu et al. (2013)).

1.4 RESEARCH OBJECTIVE AND QUESTIONS

The problems as stated in the previous section together with the rehabilitation of the former Northern Swamp as a proposed measure to mitigate these problems lead to the research objective for this research:

To evaluate the functioning of two alternative rehabilitation alternatives, with in particular the sediment trapping efficacy, by modeling the sediment inflow for various Malewa River discharges using a one-dimensional modeling approach

To clarify this research objective, the underlined phrases are explained in detail.

To evaluate the functioning of the rehabilitation alternatives, the sediment trapping efficacy will be reviewed, but also the other objectives driving this rehabilitation plan proposed by Marula Estates (2009) as presented in section 2.4.

In the context of this objective, sediment trapping efficacy is defined as the extent to which the alternative rehabilitation designs are able to trap sediment which will be expressed in the volume (m^3) trapped. Together with the sediment trapping efficacy, the sediment transport processes, such as erosion and sedimentation, taking place within the rehabilitation designs water systems will be described.

The two alternative rehabilitation alternatives are based on the Wetland rehabilitation project Naivasha – Kenya (Marula Estates, 2013) and differ in the way of landscaping the former Northern Swamp. What both alternative designs have in common is the spillway channel connecting the Malewa River and the former Northern Swamp including the inlet construction to regulate the amount of water to be diverted. The level of the base of the inlet construction however, is not incorporated in the design, and the same holds for the regulation of the inlet construction. This information is crucial to determine the sediment trapping efficacy, but since this information is lacking it is decided to model and present the sediment inflow for various Malewa River discharges.

The two main research questions answered during this study to reach the research objective are:

1. *What is the most promising rehabilitation alternative, with in particular concerning the sediment trapping efficacy?*
2. *What is the reliability of the one-dimensional modeling approach?*

The objective for which this report is written becomes twofold; firstly to describe the research and secondly to serve as a guide line from which the sediment trapping efficacy can be determined based on the discharge entering the Northern Swamp area. As soon as the inlet construction is constructed and the spillway channel is in use, depending on the inlet construction regulation, an estimate can be made about the spillway channel discharge (see section 8.2 for recommendations about what needs to be done to make such an estimate).

1.5 RESEARCH APPROACH

In order to answer the first research question:

> *What is the most promising rehabilitation alternative, with in particular concerning the sediment trapping efficacy?*

the following subjects will be discussed in detail in each chapter:

Chapter 2: the Lake Naivasha basin, Chapter 3: the rehabilitation alternatives, Chapter 4: the modeling method and Chapter 5: the input used for the modeling.

In order to answer the second research question:

> *What is the reliability of the one-dimensional modeling approach?*

the results of the modeling will discussed in chapter 6. In Chapter 7, the assumptions made during the research leading to the answers on the research questions presented in the previous chapters are critically reviewed and presented together with the impacts of these assumptions on the results. In Chapter 8 the conclusion will be presented based on the research objective, together with recommendations to improve the results of this research and suggestions for further research to improve the impact assessment of the rehabilitation plans.

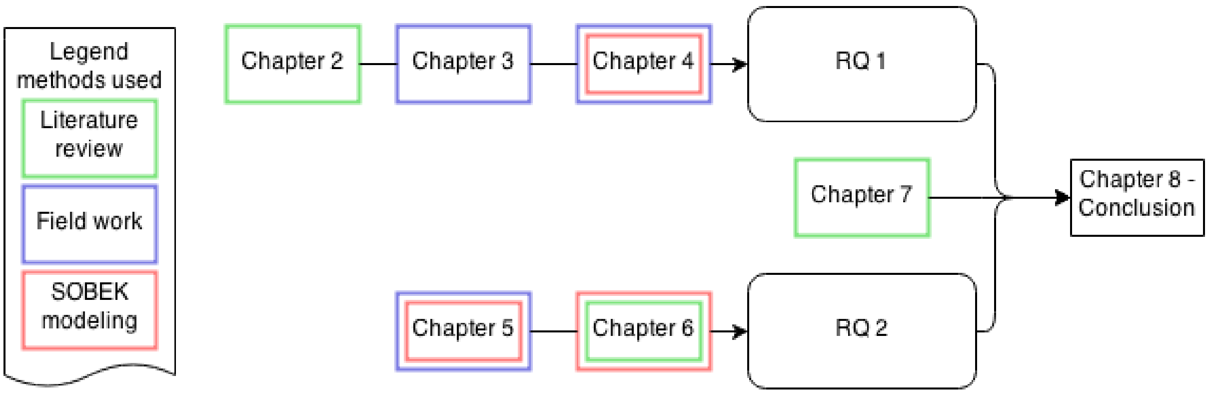


FIGURE 1: RESEARCH APPROACH AND METHODS

Figure 1 gives an overview of the research approach, which is further explained below. Several methods have been used during this research to gather the necessary information and execute the modeling. The data gathered by using the different methods (indicated by the colored boxes) included in the chapters as is described below, is used to arrive at the questions on the research questions (RQ 1 and RQ 2) which together with the discussion are merged to the conclusions for this research.

Preparatory research in the form of a literature study has been conducted, of which the objective was roughly twofold. The first objective was to get insight in the case: the Lake Naivasha basin, while the second objective was to get insight in erosion and sedimentation in reservoirs. The results of this secondary research are summarized in Cornelissen (2013), the case-study information is used for Chapter 2 and the literature review on erosion and sedimentation and reservoirs provided the necessary background information for Chapter 6, 7 and 8.

Field work has been conducted in the period May – June 2013 in close cooperation with WRMA Naivasha. The main objectives for this field work were to visit the already constructed Gilgil River Wetland to get insight in the former Northern Swamp rehabilitation plans and to gather information about the design specifications for the Malewa River Wetland as proposed by Marula Estates (2013). The information extracted from the design specifications together with the characteristics of the Malewa River system such as cross-section dimensions and sediment particle size were used during to model the system. The cross-section measurements are done with the use of an Acoustic Doppler Current Profiler (ADCP) and the results are processed with WinRiver II software. The use of the ADCP and the results presented in WinRiver II are further explained in Appendix H. The results of the fieldwork are used for Chapter 3, 4 and 5.

The modeling method as presented in Chapter 4 with the used input data presented in Chapter 5, of which the results are presented in Chapter 6, is done with the use of an integrated software package for river management called SOBEK (Deltares, 2011). One-dimensional schematizations of the two alternative rehabilitation designs are made and with the use of SOBEK, sediment transport capacity, flow velocity and water depth is calculated for different scenarios in which is varied with the hydraulic roughness and the sediment particle size.

1.6 THESIS OUTLINE

Chapter 2 gives a more detailed view on the Lake Naivasha case by elaborating on its geography, water system, soils and sediments and the Marula Estates wetlands. In Chapter 3, the two rehabilitation alternatives are presented of which the functioning is evaluated. Chapter 4 describes the modeling method with which the sediment trapping efficacy is determined, with in Chapter 5 the data used for the modeling process. The results of the modeling for the two rehabilitation alternatives are presented in Chapter 6. And since not everything can be included in a model, processes that are left out but do influence the conclusions of this research are described in Chapter 7 including their impacts. The conclusion, together with recommendations to improve the results and the use of this research and suggestions for further research are presented in Chapter 8.

CHAPTER 2 – LAKE NAIVASHA STUDY AREA

This chapter presents the Lake Naivasha Basin characteristics in more detail by describing its location, the water system, the soils and sediments and the Marula Estates wetlands.

2.1 GEOGRAPHY

Lake Naivasha is a shallow basin lake covering approximately 140 km², situated 80 km northwest of Nairobi at an altitude of 1.890 m above MSL in Africa's Eastern Rift Valley, and is the second-largest freshwater lake in Kenya (Becht et al., 2005) (See Appendix A for a more detailed overview of the location). The Aberdare mountain range bound the basin to the east, Mount Longonot to the south, the Mau Escapment to the southwest and the Eburu Mountains to the northwest (Gitonga, 1999). This system is depicted in Figure 2A.

The total basin area is about 3376 km² and consists of three major sub-catchments: the Malewa catchment (1600 km²), the Gilgil catchment (527 km²) and the Karati catchment (149 km²) (Gitonga, 1999). The lake ecosystem consists of three lakes which are the main lake, Lake Oloidien located southwest of the main lake which is, depending on the lake level, separated or not from the main lake and a detached crater lake, Lake Sonachi, to the west which is the smallest (Stoof-Leichsenring et al., 2011). The lakes including water depth/bottom levels, groundwater flow (red arrows) and flowers farms are depicted in Figure 2B.

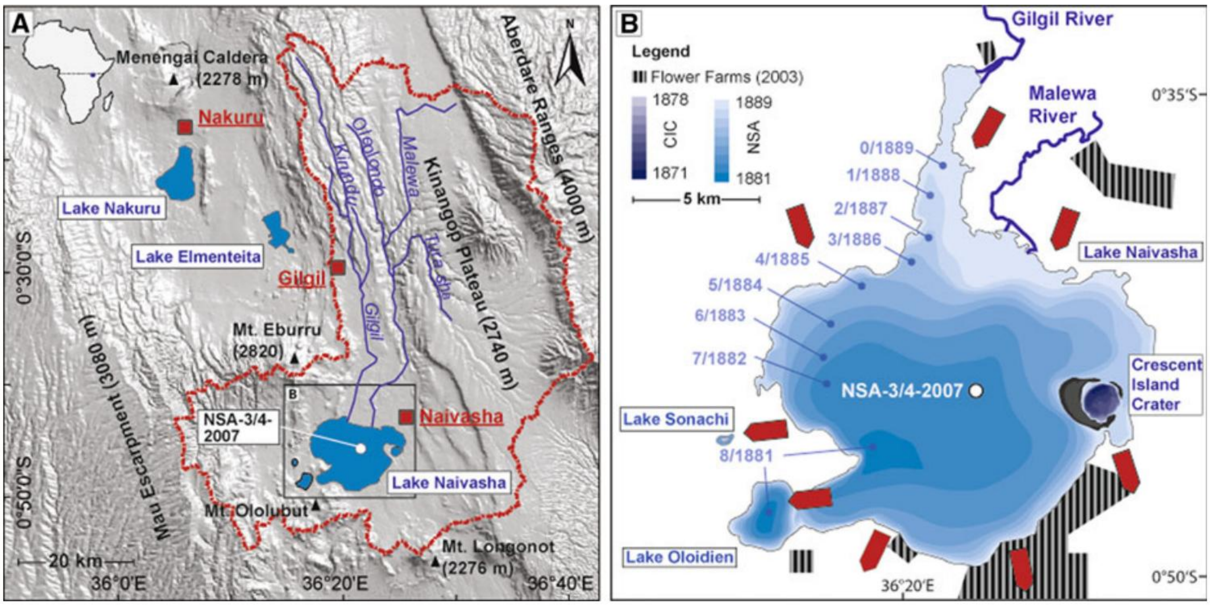


FIGURE 2: A. LAKE NAIVASHA BASIN AND SURROUNDING. B. LAKE NAIVASHA WITH DEPTH CONTOURS (WATER DEPTH/BOTTOM LEVEL), INFLOWING GILGIL RIVER AND MALEWA RIVER, FLOWER FARMS AND GROUNDWATER FLOWS (RED ARROWS) (STOOF-LEICHSENRING ET AL., 2011)

The maximum water depth of the main lake is about 8 meter and reached in the southwestern part of the main lake, and Lake Oloidien. In the northern part of the lake where the two main rivers, Malewa River and Gilgil River, flow into the lake the bottom shows a relatively gradual slope. This area used to be the Northern Swamp, where prior to entering the lake, the Malewa River used to diverge in a dendritic pattern and disappear under the floating mat of the swamp (Gaudet, 1979). These formerly extensive floating mats trapped sediments, incorporated nutrients into plant and microbial biomass and removed nitrogen by denitrification. This ecological buffer zone consisting of Cyperus papyrus plants, however, no longer exists (Morrison et al., 2009). According to Marula Estates (2009), the original 13,5 km² of swamp is reduced to only 4,5 km². According to Harper et al. (2004), the lake-wide decline of papyrus has been caused by the combination of lowered lake levels and human destruction. However, papyrus re-germinated in a band around the lake by late 2010 because of water level rise of 2 meters in just 3 months. This rapid change shows the natural hydrological instability but also the ecological resilience of the lake (Harper et al., 2011). In Figure 3 the former and current swamp are presented together with the inflowing Gilgil and Malewa Rivers.

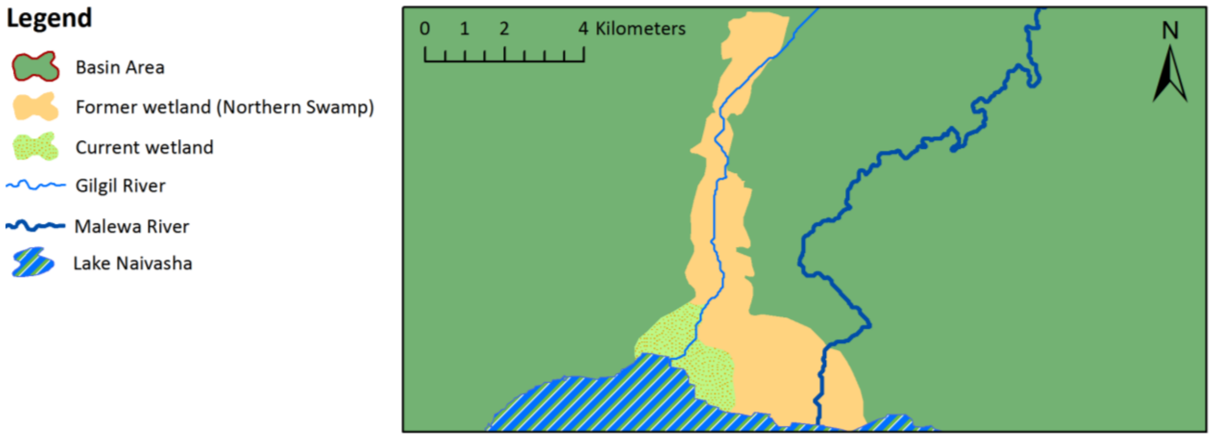


FIGURE 3: STUDY AREA WITH FORMER AND CURRENT WETLAND, GILGIL AND MALEWA RIVERS

2.2 Water system

To provide insight in the flow of water in and out of the lake, an overview of the long-term monthly averaged precipitation, evaporation and river discharge is presented. Reta (2011) collected rainfall data from the Naivasha district office meteorological station and considered this rainfall to be precipitated direct into the lake. Figure 4 presents the monthly averaged precipitation for the period 1932-2010.

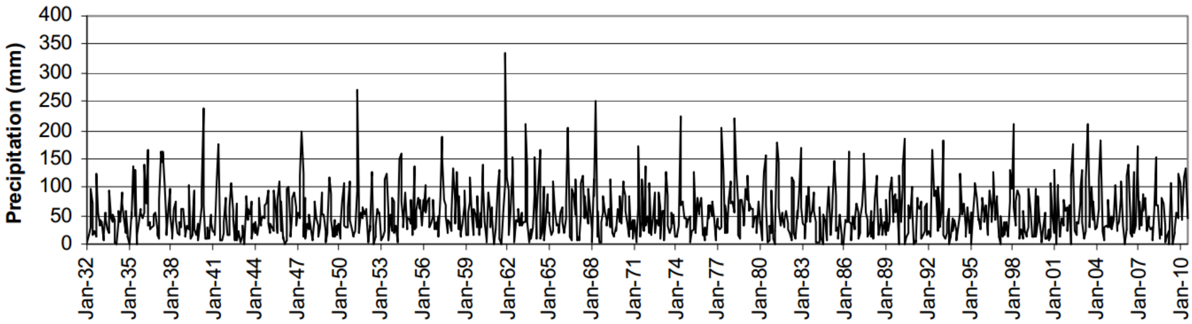


FIGURE 4: MONTHLY AVERAGED PRECIPITATION (RETA, 2011)

The monthly averaged pan evaporation determined by Reta (2011) presented in Figure 5 is based on data from the Naivasha Water development Department and from the Oserian meteorological station, a private station located on the western side of the lake.

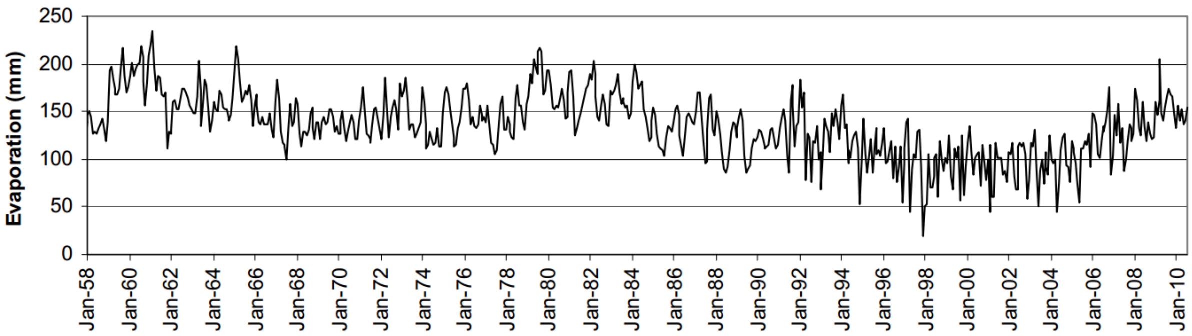


FIGURE 5: MONTHLY AVERAGED PAN EVAPORATION (RETA, 2011)

The surface water inflow was determined by Reta (2011) for the Malewa, Gilgil and Karati River. The Malewa and Gilgil River, draining the area north of the lake, discharge 80% and 20% of the total inflow respectively. The ephemeral Karati River drains the area east of the lake during approximately 2 months per year. The drainage from the area west of the lake infiltrates before it reaches the lake, while the area south of the lake does not produce much runoff reaching the lake (Becht et al., 2005). The monthly averaged surface water inflow by the Malewa, Gilgil and Karati River is presented in Figure 6.

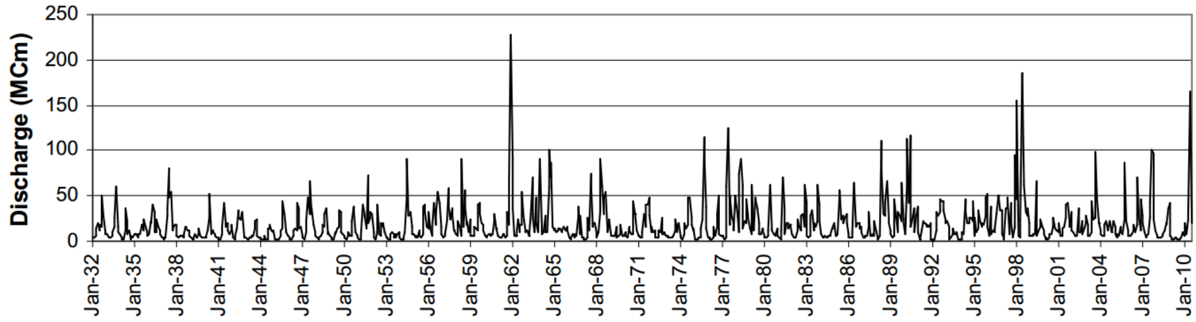


FIGURE 6: MONTHLY AVERAGED RIVER DISCHARGE (MALEWA, GILGIL AND KARATI TOTAL) (RETA, 2011)

The lake water level shows large fluctuations, as depicted in Figure 7. The relatively low water level occurring during the 1940s is caused by the climatic conditions. The decrease in water level starting from the beginning of the 1980s coincides with the commencement of horticulture. If the 1940s climatic conditions recur in combination with the current water abstractions, the lake surface area will be reduced from approximately 120 km² to 30 km² (Becht et al., 2005). Due to the relatively gradual bottom slope in the Northern Swamp, only a small fluctuation in water level leads to a large movement of the lake shoreline. This in turn has great influence on the processes concerning the inflow from the Malewa and Gilgil River.

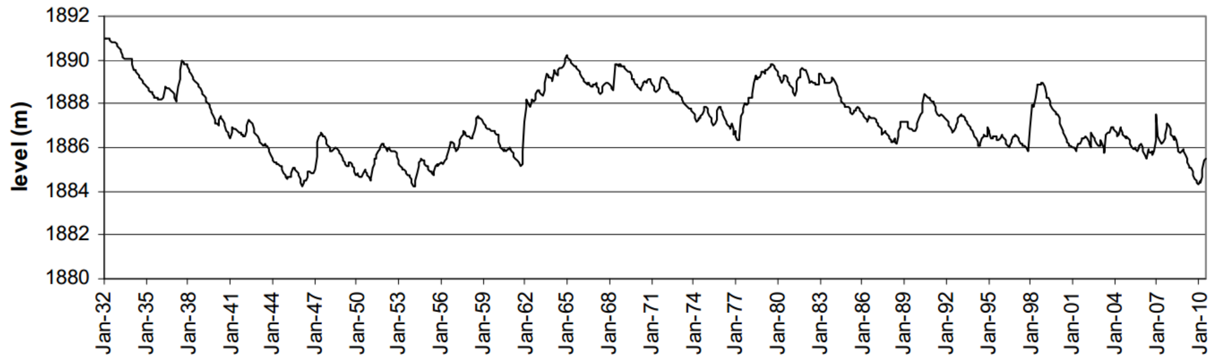


FIGURE 7: MONTHLY OBSERVED LAKE WATER LEVEL OVER TIME (RETA, 2011).

2.3 SOILS AND SEDIMENTS

The Rift Valley consists of volcanic formations, with the soils around Lake Naivasha developed on volcanic ashes. Due to the high pumice content, the soils around the lake are very permeable and have a very low water-holding capacity. Consequently, water seeps quickly to depths below the plant rooting zone and very frequent irrigation activity is necessary (Becht et al., 2005).

According to Zink (1988) as stated in Siderius et al. (1999), two main landscapes can be identified in Lake Naivasha area which are the volcanic plains and the lacustrine plains. The volcanic plains result from the lava flow from Longonot and pyroclastic materials deposited by the wind. The lacustrine plains are covered with sediments derived from erosion of the surrounding volcanic rocks of the rift margins. Girma et al. (2001) unified several disparate studies on the soils in the Lake Naivasha area. They present a more detailed geopedologic map which includes, besides the already mentioned volcanic and lacustrine plains, five more major landscape units in the Naivasha.

Physical and chemical river sediment characteristics could be, due to downstream transport and mixing, related to the activities undertaken and processes occurring in the catchment area (Levinson, 1974). Tarras-Wahlberg et al. (2002) took sediment samples from the rivers and the lake, and examined them physically and chemically. They conclude that sediment dynamics are governed by the presence of river point sources in the north. Deposition of silt and sand sized material takes place near the river outlets, after which due to wave-induced re-suspension these materials are being transported in easterly and southerly directions and deposited in the lake's central, southern and eastern parts.

2.4 MARULA ESTATES WETLANDS

In 2009, Marula Estates, on its own initiative, performed a study (Lake Naivasha Wetland Restoration Project Naivasha - Kenya by Marula Estates (2009)) on the current state of the former Northern Swamp, from which became clear that of the former 13.5 km² only less than 4.5 km² hectares were still intact as wetland. This led to the development of a plan to rehabilitate the Northern Swamp in order to (Marula Estates, 2009):

- Prevent the siltation of Lake Naivasha,
- Reduce pollution and excess nutrients reaching the lake,
- Making the Kenyan public aware about the importance of wetlands by using this project as an example of rehabilitation,
- Re-establish the original north lake wetland,
- Maximize the biodiversity in the Naivasha northern area,
- Encourage the best use of wildlife conservation,
- Create a roosting area for migratory birds,
- Enhance tourism in Naivasha and
- Re-establish the former permanent vigorous Papyrus ecosystem.

2.4.1 GILGIL RIVER WETLAND

The restoration project consists of multiple phases. The first phase of this project was to rehabilitate the northern part of the former Northern Swamp where the Gilgil River enters and is executed in 2009 with the construction of a fish ladder and earthmoving works to maximize the ecosystem's biodiversity. An area of about 1.4 km² was rehabilitated which led to an increased number of bird species (+45%) and large mammals (+92%) present in the area over a period of approximately 13 months (Marula Estates, 2009). The results of the rehabilitation of the Gilgil wetland are presented in more detail in Appendix B.

2.4.2 MALEWA RIVER WETLAND

The positive results of the first phase of the rehabilitation project have encouraged the implementation of the second phase of the project, which comprises the rehabilitation of an additional 7,6 km² wetland fed by the Malewa River. The first and second phase of the project together with the results of phase 1 and the expected results of phase 2 are presented in Figure 7. The second phase of the restoration project comprises three main components which will be described in general in this section. A detailed elaboration of the design with its specifications can be found in Appendix C. The first component is the construction of an earth dike including a fish ladder functioning as outlet construction. The length of the embankment will be 1.625 m, with a width on top of 8 m and a maximum level of 1955.30 m above MSL. The construction costs are estimated at approximately €50.000 including engineering, earthwork shaping and vegetation planting. The fish ladder is a 42 m long, approximately 15 m wide 137 m³ reinforced concrete construction consisting of five steps with the spillway level at 1954.30 m above MSL. The costs are estimated at €70.000 including engineering, materials and earthworks.

The second component is shaping the landscape for maximizing the wetland biodiversity which will be done on 1,2 km² and includes the construction of small islands of various levels to maximize biodiversity and natural colonization of different plants according to the specific water level. The costs of soil movement, land shaping, vegetation planting and survey of the site are estimated at €160.000.

The third component is the construction of the Malewa spillway channel including the construction of the inlet construction in the Malewa River bank to divert the water from the Malewa River into the wetland. The spillway channel will have a length of 2.150 m, a bottom width of 3 m, a depth varying from 1.5 till 4 m, river bank slopes of approximately 45⁰ and thus cross-section surface areas ranging from 6.75 till 28 m². The spillway channel bed slope will be approximately 0.3% and the excavated soils will be used to create a dike of 1.75 m height next to the channel. The costs of engineering, excavation and vegetation rehabilitation are estimated at €120.000. The costs of the inlet construction are estimated at €85.000 and include engineering and soil excavation. The structure consists of four sluice gates of 1.15 m width and 2.45 m height, manually closeable individually with four iron doors which can be operated from the bridge crossing the four sluice gates. The 85 m³ reinforced concrete structure has a width of 12 m, length of 14 m and a height of 6.3 m.

The earth dike, spillway channel and the location of the inlet and outlet construction, together with the expected results are shown in Figure 8.

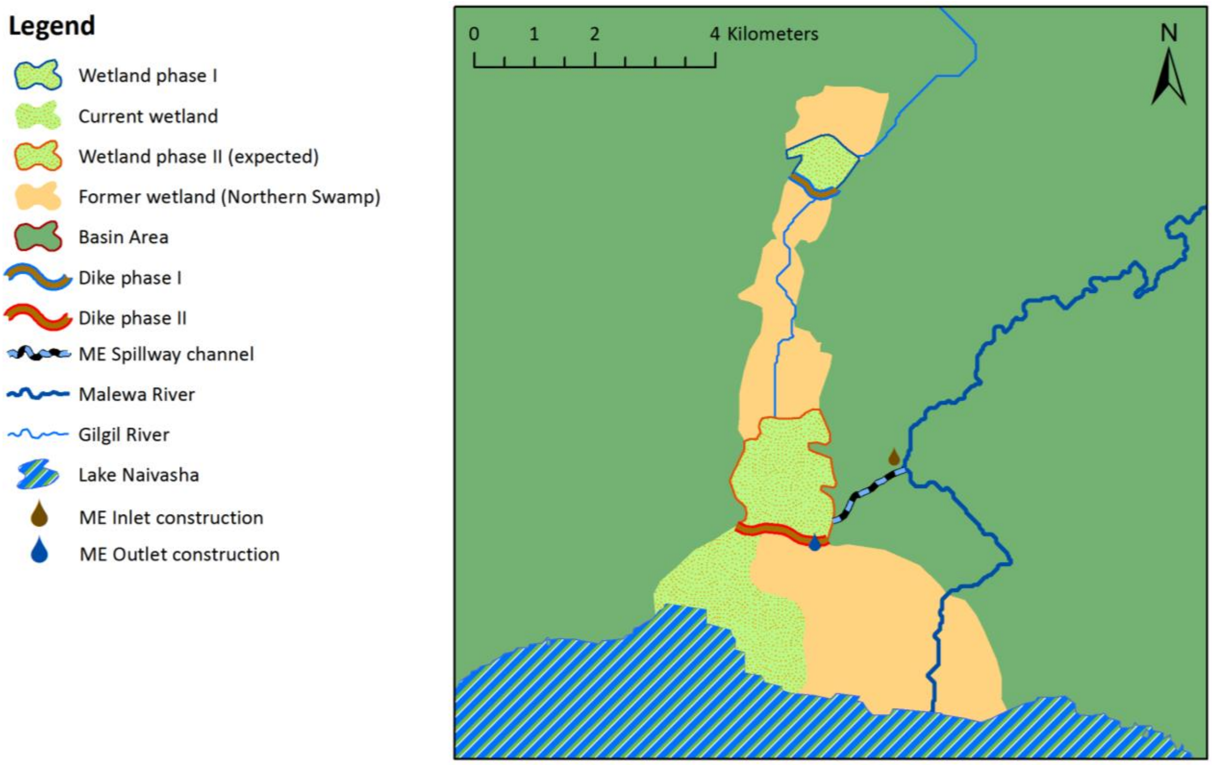


FIGURE 8: STUDY AREA INCLUDING RESULTS PHASE I AND (EXPECTED RESULTS) PHASE II MARULA ESTATES DESIGN

CHAPTER 3 – REHABILITATION ALTERNATIVES

This chapter presents the design alternatives and its characteristics in general. To model the system, assumptions on the dimension have been made, which are presented in Chapter 4.
The alternatives are based on the Marula Estates design, but have one major change in common compared to the Marula Estates design, which is the relocation of the inlet construction and the spillway channel which will be described in the first section. Then an overview of both rehabilitation alternatives will be presented. To conclude, other objectives as are described in Chapter 4 (extracted from Marula Estates (2009)) will be discussed briefly, since sediment trapping efficacy is not the only objective of the rehabilitation project.

3.1 MARULA ESTATES DESIGN RECONSIDERATIONS

The design alternatives presented in this chapter are all based on the design presented by Marula Estates (section 2.4) (Marula Estates, 2013). The two different design alternatives have in common that one major modification is made, which is the relocation of the inlet construction and the spillway channel. The location of the inlet construction and the spillway channel proposed by Marula Estates is depicted in Figure 9 by the blue/black dotted line, while the new proposed location is depicted by the orange/black dotted line. The brown droplet indicates the location of the inlet construction, and the blue droplet indicates the outlet construction.

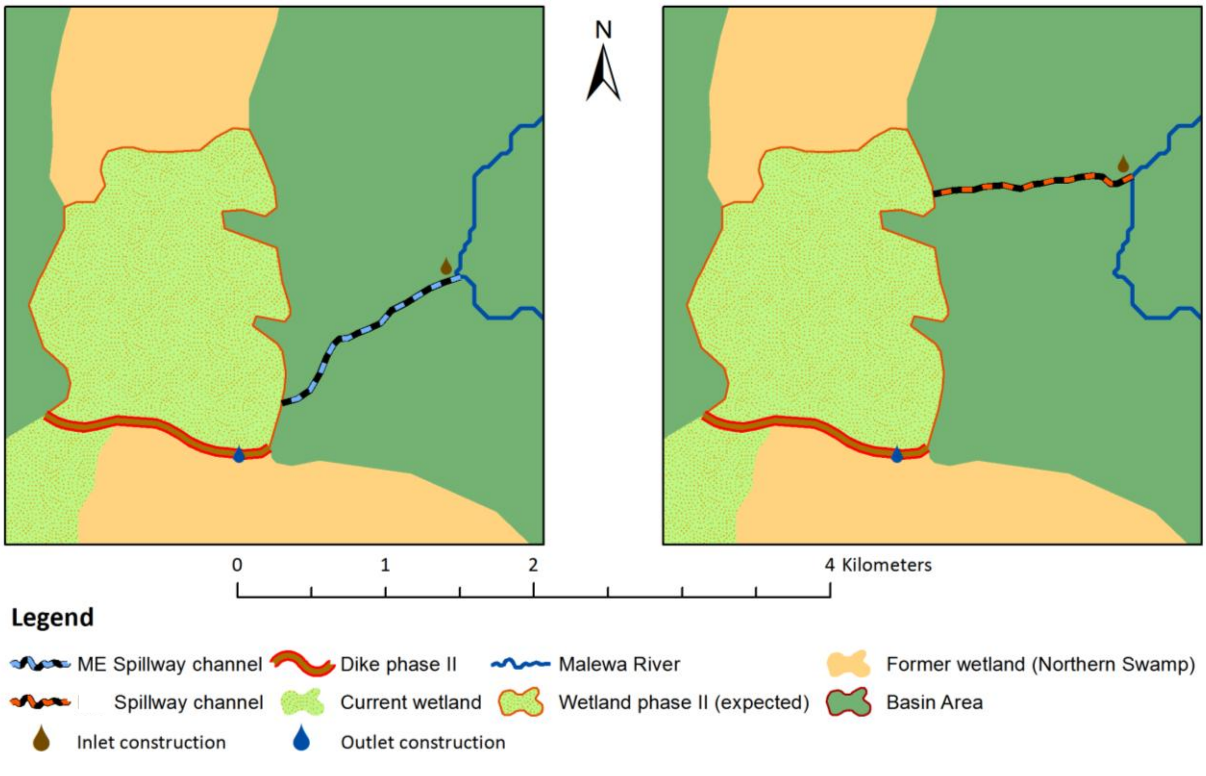


FIGURE 9: MARULA ESTATES (ME) DESIGN (LEFT) RECONSIDERATION AND MODIFICATIONS (RIGHT)

The relocation of the spillway channel is suggested to improve the use of the area made available by Marula Estates. The first improvement is the larger area that becomes available on which sedimentation can take place by relocating the spillway channel northwards. In the original design, the spillway channel enters very close to the outlet construction due to which sedimentation takes place concentrated in that area. Due to the outlet construction and the low flow velocities the sediments pile up. When too much sediments pile up, the flow velocities will increase again and the sediments will be transported over the outlet construction. This way, the sediment trapping efficacy is small and the sediments are likely to clog the outlet construction. By moving the mouth of the spillway channel northwards, a larger area becomes available over which the sediments can be deposited.

Another advantage of moving the spillway northwards is the usage of the former Northern Swamp area during times of high lake water levels such was the case during the field work period (May – June 2013). During high water levels, both the Malewa River and the spillway channel will discharge directly into the lake and therefore no sediments will be trapped in the rehabilitated area. By relocating the mouth of the spillway channel northwards, sediments can be trapped also during high lake water levels. Also in times of low lake water levels and low Malewa and Gilgil River discharges, moving the mouth of the spillway channel seems to be beneficial. In dry periods, only small amounts of water will flow from the Gilgil Wetland into the direction of the lake. This is caused by increased water abstractions from the Gilgil River in its catchment which results in a decreased discharge entering the Gilgil wetland and increased evaporation from the Gilgil wetland. Due to this decreased Gilgil River discharge, the area between the Gilgil Wetland and the lake becomes dryer. By relocating the spillway channel mouth northwards, a certain amount of the Malewa River discharge, to be controlled with the inlet construction, can be used to provide this area with water in order to comply with the objectives such as maximizing biodiversity and enhancing tourism.

3.2 WETLAND ALTERNATIVE

The Wetland alternative is based on the design as proposed by Marula Estates (2013) and its characteristics are extensively discussed in section 2.4. Its sediment trapping functioning is based on a basic principle: discharge (Q [m³/s]) equals flow velocity (u [m/s]) times cross-section surface area (A [m]): $Q = u * A$. For a certain discharge a drop in flow velocity occurs when the water enters the wetland with its large cross-section, and therefore the sediment transport will decrease and the sediments will settle. Since sediment trapping efficacy is not the only objective of the rehabilitation of the former Northern Swamp, other objectives as are described in Chapter 4 (extracted from Marula Estates (2009)) will be discussed briefly. A schematic overview of the Wetland alternative is already presented in Figure 9, a more natural overview with the wetland in its environment is presented in Figure 10.

FIGURE 10: WETLAND ALTERNATIVE OVERVIEW

3.3 MEANDER ALTERNATIVE

The basic idea behind the functioning of the Meander alternative as a sediment trap is lowering the flow velocity by decreasing the bed slope. By creating this meandering pattern, the overall bed slope from inlet to outlet construction becomes 0.0012, while the Malewa River bed slope downstream of the inlet construction is approximately 0.0022 (see Appendix M). The spillway channel and meander cross-section however, is smaller compared to the Malewa River cross-section and therefore to realize these lowered flow velocities, proper management of the inlet construction is essential. By letting in a small discharge, flow velocities will stay limited and sediments will settle within the meander. By letting in a large discharge, the spillway channel and meander will flood and the sediments can settle on the floodplains. By high discharges, but still low enough to stay within the spillway channel and meander, sediments will be picked up and transported into the lake.

The meander alternative is presented in Figure 11. The meander channel will not reach the lake via a visible surface flow. Between the meander and the lake, water hyacinth is present in abundance (observed during fieldwork) underneath which the inflow takes place.

FIGURE 11: MEANDER ALTERNATIVE OVERVIEW

3.4 SCREENING ALTERNATIVES

Since sediment trapping efficacy is not the only objective of the rehabilitation of the former Northern Swamp, the other objectives will be briefly discussed for both alternatives.

Two other important aspects that need to be taken into account are maintenance and infiltration. While infiltration of water will be negligible in the Meander alternative, in the Wetland alternative infiltration will take place. During the fieldwork for this research, an infiltration test is done which resulted in an infiltration rate of approximately 12 cm/day (Appendix L). While the water in Lake Naivasha is used for several purposes by multiple stakeholders, the water from the wetland that infiltrates is not accessible anymore for all of those stakeholders.

Depending on the discharge entering the spillway channel and the wetland/meander, depending on the alternative, amounts of sediment settle in the former Northern Swamp. In the Meander alternative, after a while these sediments will create smaller cross-sections and therefore the sediments will be transport further downstream. In the Meander alternative it is also possible to 'flush' the channel by allowing a large discharge to enter through the inlet construction. Flushing the channel however is not desirable because the sediments still end up in the lake. The sediments trapped in the Wetland alternative can be removed by dredging, removing the soils with the use of excavators. This way the sediments do not end up in the lake, but these dredging activities will damage the vegetation and disturb the wildlife.

TABLE 1: REULTS OF FIRST SCREENING ALTERNATIVES BASED ON MARULA ESTATES OBJECTIVES

<table>
<tr><th>Wetland alternative</th><th>Meander alternative</th></tr>
<tr><td colspan="2">Reduce pollution and excess nutrients reaching the lake</td></tr>
<tr><td>(Constructed) wetlands are proven to be useful for the uptake of nutrients (Fisher et al., 1999; Loucks et al., 2005; Vymazal, 2007)</td><td>Natural streams, such as the Meander alternative, are more able to take up nutrients compared to channelized streams due to increased residence time by reduced water velocity and greater stream length (Bukaveckas, 2007). Residence time in Wetland alternative however is likely to be higher and therefore will be more successful in nutrient removal.</td></tr>
<tr><td colspan="2">Making the Kenyan public aware about the importance of wetlands by using this project as an example of rehabilitation</td></tr>
<tr><td colspan="2">To make the Kenyan public aware of solely the importance of wetlands, the Wetland alternative is best. However when the objective is broadened and would be to make the Kenyan public aware about water system rehabilitation, and thus make no distinction between swamp rehabilitation or channel rehabilitation, both the alternatives would be able useful to accomplish this objective. What then favors the Meander alternative is the absence of hard structures, such as the inlet and outlet construction in the Wetland alternative. This also gives this alternative, the meander its freedom to follow its natural course over time.</td></tr>
<tr><td colspan="2">Re-establish the original north lake wetland</td></tr>
<tr><td>The Wetland alternative makes it possible, by proper management of the inlet construction in combination with the outlet construction, to keep the former Northern Swamp inundated.</td><td>Inundation of the former Northern Swamp is more difficult to realize, this is only possible by allowing a large discharge through the inlet construction due to which the spillway channel/meander will flood.</td></tr>
<tr><td colspan="2">Maximize the biodiversity in the Naivasha northern area</td></tr>
<tr><td colspan="2">Both alternatives make it possible to maximize biodiversity by creating islands and river banks with different levels and slopes to establish the optimum conditions for the development of water plants and semi-dry land plants. The Wetland alternative however gives more opportunity to create these islands and slopes, and a greater surface of the former Northern Swamp can be inundated compared to the Meander alternative.</td></tr>
<tr><td colspan="2">Encourage the best use of wildlife conservation</td></tr>
<tr><td colspan="2">From Marula Estates (2009) it does not become clear how 'the best use of wildlife conservation' is defined. However, conservation commonly implies human intervention which becomes harder in the Wetland alternative due to the large inundated area. In the Meander alternative it is easier to intervene since the area is more accessible, e.g. to guide animals through the area to specific places in order to e.g. control the spread of diseases.</td></tr>
<tr><td colspan="2">Create a roosting area for migratory birds</td></tr>
<tr><td colspan="2">The Wetland alternative provides safe places, the islands, for the birds to roost without being threatened by other animals. The Wetland alternative provides less of these safe spots.</td></tr>
<tr><td colspan="2">Enhance tourism in Naivasha</td></tr>
<tr><td colspan="2">Both alternatives make it possible to enhance tourism in Naivasha, however the Meander alternatives makes it better possible to separate the area into areas for tourism and areas occupied by wildlife.</td></tr>
<tr><td colspan="2">Re-establish the former permanent vigorous Papyrus ecosystem</td></tr>
<tr><td colspan="2">To re-establish the former permanent vigorous Papyrus ecosystem the Wetland alternatives provides the best environment. The large area covered with water provides the right circumstances for Papyrus to grow. This is not the case for the Meander alternative.</td></tr>
</table>

CHAPTER 4 – MODELING METHOD

This chapter describes the modeling method. First an overview of the modeling method will be presented, of which the different components will be explained in detail in the subsequent sections. This chapter concludes with the assumptions made during the modeling and the consequences.

4.1 MODELING OVERVIEW

To get insight in the sedimentation processes in the spillway channel and the wetland/meander, the sediment load entering the system is modeled together with the sediment transport capacity of the system. By comparing these two an estimate is made about whether or not sedimentation is going to take place and where. To estimate the sediment load, a model developed by Syrén (1990) is used. The sediment transport capacity is calculated with the use of an integrated software package for river management called SOBEK.

To get insight in the variation in the results caused by the uncertainty in the average grain size and the hydraulic roughness, the simulations in SOBEK are done with estimated values for average grain size and hydraulic roughness, but also with extreme, but plausible, values.

4.2 SEDIMENT LOAD

The transport of sediment particles in water can be in the form of bed load, suspended load and wash load (van Rijn, 1984). Wash load tends to be uniformly distributed over the water column, since it does not rely on mechanical turbulence generated by flowing water to be kept in suspension, and therefore its concentration is also measured when measuring the suspended sediment concentration (Hickin, 1995).

To determine the suspended sediment load, a study by Syrén (1990) provides the necessary information. This study focuses on the relationship between the discharge and the suspended sediment concentration in the Malewa River. During the period from 1949 to 1957, 251 values of instantaneous sediment concentrations and discharge were gathered at gauge station 2GB01 (see Appendix D for its location) in the Malewa River. Measurements during high water discharges were not always possible (problems also described by Meins (2013)) resulting in only a few sediment sampling occasions representing these high river discharges. Only 8 out of 251 samples refer to water discharges exceeding 40 m³/s. The sediment load however is increased since 1957 (Everard et al., 2002; Harper et al., 2004; Rupasingha, 2002) and has even further increased from the late nineties to 2006 (Stoof-Leichsenring et al., 2011). This increase in sediment load and its impact on the sediment inflow is further discussed in Chapter 7.

To establish the relationship between water discharge (Q) and sediment concentration (S_c) the least square regression of concentration on discharge is used by Syrén (1990). To describe the non-linear relationship between the discharge and sediment concentration a power function is used which is considered to be the best estimate of transported suspended load (Syrén, 1990). The coefficient (a) and exponent (b) are tested by iteration until the least sum of squares of the residuals (the difference between measured and modeled sediment concentration) is obtained.

$$S_c = a * Q^b \qquad a = 26.44, b = 0.65$$

With S_c in mg/l and Q in m³/s. Based on this equation, an estimation of the suspended sediment load can be made with the use of the equation with SL in tonnes/day, Q in m³/s and S_c in mg/l:

$$SL = Q * S_c * 0.0864$$

4.3 SOBEK MODEL

To model the sediment transport capacity within the spillway channel and wetland/meander, an integrated software package for river management called SOBEK is used. SOBEK has three basic product lines consisting of different modules to simulate particular aspects of the water system. For this research, the SOBEK-Rural line is used with the 1DFLOW hydrodynamics module.

The user-interface of SOBEK consists of blocks which each represent a specific task. These blocks with their tasks are presented in Figure 12. The arrows between the blocks represent the relation between the tasks and the sequence in which they have to be executed. For each of the blocks a short explanation is presented about its function.

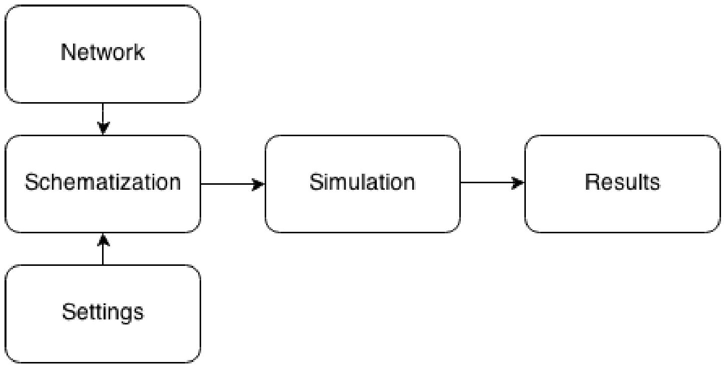


FIGURE 12: SOBEK USER-INTERFACE WITH TASK BLOCKS

Network: with the use of this block, an already defined network, containing the schematization of the real-world water system with its characteristics such as cross-section dimensions, channel lengths, river bed slopes and roughness, can be uploaded.

Settings: this block contains settings such as average grain size, water density and gravitational acceleration, but also simulation settings such as the computation time step, the simulation period and the output parameters.

Schematization: this block allows the user to set up and make changes to a schematization with the help of the network editor.

Simulation: in this block the calculations on flow velocity, water depth and sediment transport capacity are performed. The equations used to perform the calculations are explained in Appendix E.

Results: The results of the simulations are exported as data sheets containing the modeled values for sediment transport capacity, flow velocity and water depth.

For both alternatives, to model the sediment inflow, the upstream boundary condition is a constant discharge of 25 m^3/s. To model the sediment transport processes within the spillway channel itself, the upstream boundary condition is a discharge varying from 0 till 100 m^3/s.

Every 200 m a calculation point is inserted in the SOBEK to extract the hourly calculated data at these points and the reach in between these points. At these calculation points the water depth is calculated, and on the reaches in between these points the flow velocity and the sediment transport capacity.

The two rehabilitation alternatives as they are modeled in SOBEK are presented in Figure 14 and Figure 15, with in Figure 13 the dimension of the cross-sections.

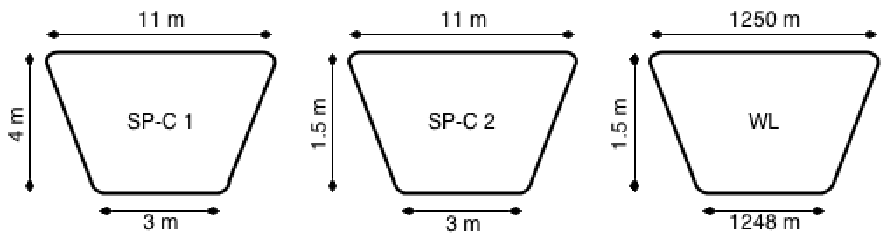


FIGURE 13: CROSS-SECTION DIMENSIONS

Figure 14 presents the Wetland alternative as it is modeled in SOBEK. The inlet construction is located at 1960.8 m above MSL from where the spillway channel starts with its largest cross-section (SP-C 1: spillway channel cross-section 1). Over the length (2150 m) of the spillway channel, with a bed slope of 0.003, the cross-section narrows to SP-C 2 (SP-C 2: spillway channel cross-section 2). From there the spillway channel enters the wetland (WL: wetland). The lowest point of the outlet construction is constructed at 1954.3 m above MSL, thereby creating a maximum water level in the wetland of 1 m.

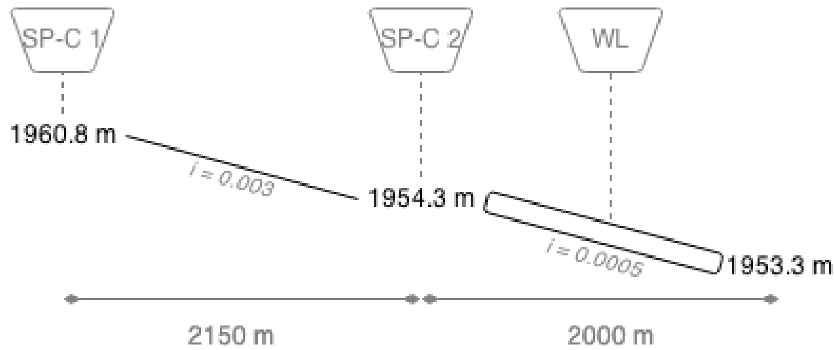


FIGURE 14: SCHEMATIZATION WETLAND ALTERNATIVE

Figure 15 presents the Meander alternative as it is modeled in SOBEK. Again the inlet construction is located at 1960.8 m above MSL from where the spillway channel starts with its largest cross-section (SP-C 1: spillway channel cross-section 1). Over the length (2150 m) of the spillway channel, with a bed slope of 0.0012, the cross-section narrows to SP-C 2 (SP-C 2: spillway channel cross-section 2). From there, the meander stretches out over a length of 4000 m with the SP-C 2 cross-section. The meander does not start at the same level as the wetland in the Wetland alternative. This is because for the Meander alternative, the slope over both the spillway channel and the meander is assumed to be equal, which is 0.0012 ((1960.8-1953.3)/6150=0.0012). The length of the spillway channel is also assumed to be equal for both alternatives, 2150 m, and therefore the meander in the Meander alternative starts at a higher level compared to where the wetland starts in the Wetland alternative.

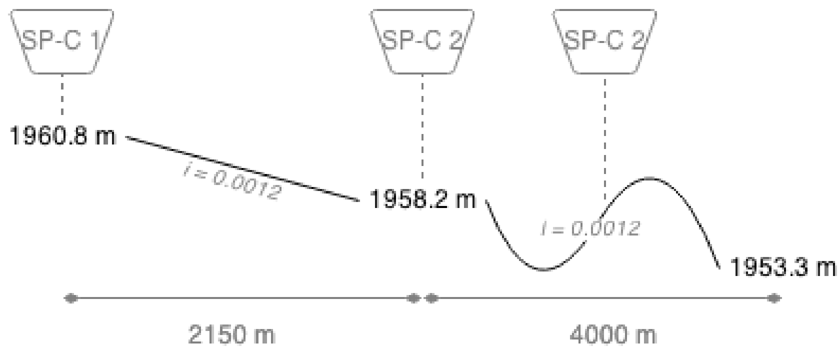


FIGURE 15: SCHEMATIZATION MEANDER ALTERNATIVE

4.4 MODELING ASSUMPTIONS

During the modeling, assumptions have been made that have impact on the results. Assumptions have been made for the modeling of the inflow of sediments and for the schematization of the system in SOBEK.

To estimate the inflow of sediments, the model developed by Syrén (1990) is used. This model is developed based on data consisting of measurements done during relatively low discharges, only 8 out of 251 samples refer to water discharges exceeding 40 m^3/s (Syrén, 1990). Therefore the uncertainty in the modeled discharge increases with increasing discharges, discharges during which the sediment transport is relatively high.

The schematization of the water system in SOBEK is only an approximation of the water system as it is in the real world. The spillway channel cross-sections are schematized in the way as they are presented in the Wetland rehabilitation project Naivasha – Kenya (Marula Estates, 2013) and thus likely are going to be constructed in the future. The wetland area in the Wetland alternative however, is schematized as a wedge with a length of 2000 m, a width of 1250 m and a depth varying from 0 till 1.5 m.

The schematization of the system in SOBEK is also one-dimensional. Due to this, important sediment transport processes typically taking place in meandering channels such as erosion in the outer bends and sedimentation in the inner bends are not taken into account.

Not only is the schematization of the water system in SOBEK only an approximation of the water system as it is in the real world, the real world water system itself is subject to constant both temporal as well as spatial changes. The complex system of small islands and small channels in the wetland (Figure 16) is constantly changing due to sediment transport and the movements of animals, and the meander will shift through the landscape due to erosion of the outer bends and sedimentation in the inner bends (Bolla Pittaluga et al., 2009; Lancaster et al., 2002). These processes are further discussed in Chapter 7.

Another assumption is that the hydraulic roughness is equal over the complete water system, while in reality this varies temporally and spatially. The hydraulic roughness varies due to smaller obstacles, such as the formation and movements of bed-forms, vegetation, but also larger obstacles such as piles of trees (Figure 17).

FIGURE 16: WETLAND ISLANDS AND SMALL CHANNELS

FIGURE 17: HYDRAULIC ROUGHNESS; PILE OF TREES

CHAPTER 5 – DATA

This chapter describes the data used in the modeling process. A distinction is made between the hydrological and hydraulic data such as discharge and channel dimensions, and the sediment characteristics data such as particle size diameter.

5.1 HYDROLOGICAL AND HYDRAULIC DATA

5.1.1 DISCHARGE

In order to get insight in the Lake Naivasha basin water system, WRMA monitors 15 river gauging stations throughout the basin, from which station 2GB01 is closest to the inlet construction (a schematic overview of the locations of the river gauging stations can be found in Appendix D). With the use of the water levels measured at the gauging stations and rating curves, stream flows can be calculated. However, as mentioned in Meins (2013), due to circumstances such as broken gauging staffs and unreliable readings no complete discharge series could be developed. One of the results of the study done by Meins (2013) are interpolated discharge series for 2GB01. Two methods of interpolation are used, further referred to as the interpolation method (method based on data from gauging station 2GB05 and 2GC04) and the fully interpolation method (method based on data from gauging station 2GB01). A detailed description of the interpolation methods can be found in Meins (2013). Both the interpolated and fully interpolated discharge series are presented in Appendix F, from which it can be noticed that both show the same pattern, however the latter estimates the peak discharges somewhat lower. Since generally the sediment transport increases with increasing discharge, which is also the case for the Malewa River according to Syrén (1990), peak discharges are important to this study and therefore the interpolated discharges series will be used.

Based on the water allocation plan presented by the Water Resources Management Authority (Water Resources Management Authority, 2010), in which a flood flow is defined as the flow being exceeded only 20% of the time (Q_{20} flow). Based on a Q_{20} flow and the interpolated discharge series, a peak flow is defined as a discharge exceeding 10.6 m^3/s. The flow duration curve including the Q_{20} - flow are presented in Appendix G.

5.1.2 WATER SYSTEM DIMENSIONS

The spillway channel dimension are included in the Wetland rehabilitation project Naivasha – Kenya document (Marula Estates, 2013) and are presented in Figure 13, with spillway channel cross-section 1 (SP-C 1) the dimensions near the inlet construction and spillway channel cross-section 2 (SP-C 2) the dimensions near the wetland area.

The wetland dimension for the Wetland alternative are based on the Wetland rehabilitation project Naivasha – Kenya document (Marula Estates, 2013) with some modifications and assumptions. The width of the wetland area is estimated at 1250 m and the length at 2000 m. The depth varies from 0 m at the location where the spillway channel enters the wetland area till 1 m depth near the outlet construction. The level of the outlet construction however is set at 1 m from the wetland bottom, which means that the earth dike in which the outlet construction is going to be constructed exceeds in height with 0.5 m above the maximum wetland water level.

The meander in the Meander alternative has a length of approximately 4000 m, and the cross-section is equal to spillway channel cross-section 2 (SP-C 2).

5.1.3 ROUGHNESS

Hydraulic roughness is the measure of the amount of resistance that water experiences when flowing through the water system, which in this case is the spillway channel and the wetland. The hydraulic roughness gets determined by the grains covering the river bed and the bed forms developed by the movements of these grains, but also vegetation and even larger objects such as bridge piers, or in this case the inlet construction.

To model the hydraulic roughness of the water system, Manning's 'n' values are used. To determine the values resembling this specific water system, observations during the field work are used in combination with a table describing the type of channel and their representative Manning values made by Chow (1959). Chow (1959) describes 'earth excavated or dredged winding and sluggish channels' with different forms of vegetation and from this description the following values are extracted to characterize this water system:

TABLE 2: HYDRAULIC ROUGHNESS VARIATION SCENARIOS

Scenario	2a	0	2b
Hydraulic roughness (n)	0.030	0.035	0.040

5.2 SEDIMENT CHARACTERISTICS DATA

No detailed studies have been done on the physical characteristics, such as the particles size, of the river sediments. During the field work, one sediment sample is taken from the bed of the Malewa River at location 'River straight' as indicated in Appendix H. The sample is taken from the bottom, near the river bank, during a relatively low discharge of approximately 2.5 m^3/s. Oven drying the sample and sieving it resulted in the particle size distribution presented in Figure 18. The sample is sieved at the fractions 0.05, 0.10, 0.25, 0.50, 1.00 and 2.00 mm, with which approximately 95% of the weight of the sample was classified.

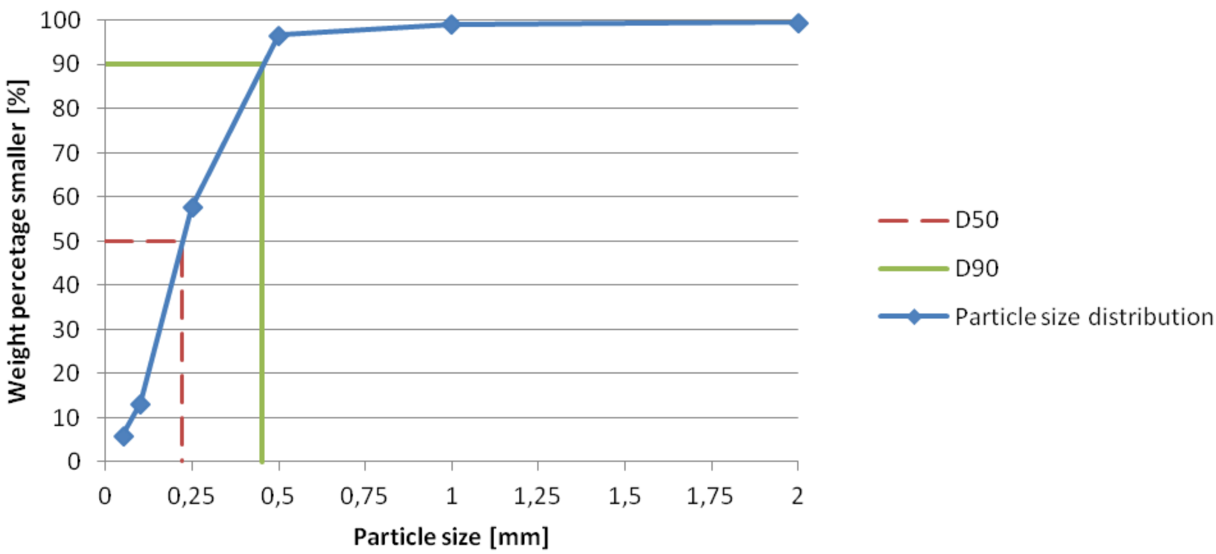


FIGURE 18: SEDIMENT PARTICLE SIZE DISTRIBUTION

To get an idea about the range of the sediment particle size, particle size distributions are made based on sediment samples (samples taken at North-East transect at the levels 1882, 1883 and 1884 m asl: NE1882, NE1883 and NE 1884) taken in Lake Naivasha itself near the mouths of the Malewa and Gilgil River. These particle size distributions are presented in Appendix I. Based on these distributions, the range in sediment particle size is estimated for D50. To estimate D90, the same rate between the estimated values for D50 and D90 is assumed. Table 3 presents the range in particle size distribution.

TABLE 3: PARTICLE SIZE VARIATIONS SCENARIOS

Scenario	1a	0	1b
D_{50} [mm]	0.063	0.22	1.00
D_{90} [mm]	0.13	0.45	2.05

CHAPTER 6 – RESULTS

In this chapter, the results of the calculations on sediment inflow and the results of the modeling in SOBEK are presented and clarified. The results are presented for the estimated values for roughness and average grain size, but also for the extreme values of these two parameters. The results are presented for a varying Malewa River discharge, but for a constant discharge diverted through the inlet construction in this Chapter.

6.1 SEDIMENT INFLOW

The inflow is determined for the year 2010 based on the interpolated discharge series for 2GB01 (Meins, 2013). The level of the inlet construction is not specified in the Wetland rehabilitation project Naivasha - Kenya document (Marula Estates, 2013). But, because the depth of the Malewa River at the location of the inlet construction is approximately 9-10 meters, and the height of the inlet construction is approximately 4 meters, it is most feasible and sensible and therefore likely that the base of the inlet construction is going to be constructed at approximately 6 meters height from the Malewa River bed (Figure 19). To determine the inflow for 2010, a discharge rating curve, presented in Appendix J, is made for Malewa River at the location where the inlet construction is going to be constructed. From this discharge rating curve is extracted that a water height exceeding 6 meters represents a discharge exceeding approximately 60 m³/s. The inflow of water and sediments in case the inlet construction is going to be constructed lower, e.g. at 3 meters above the river bed, is presented in Appendix K.

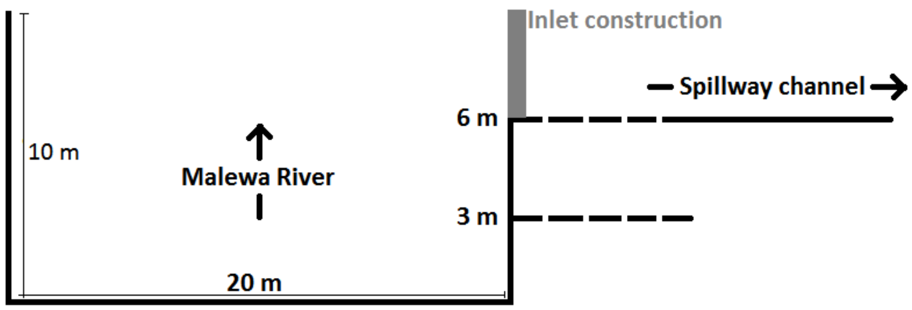


FIGURE 19: INLET CONSTRUCTION CONNECTING MALEWA RIVER AND SPILLWAY CHANNEL

The suspended sediment transport is based on the relationship between discharge and suspended sediment transport developed by Syrén (1990). The power regression model used to calculate the sediment concentration S_c in mg/l and Q in m³/s, together with the values for the coefficient and exponent are:

$$S_c = a * Q^b \qquad a = 26.44, b = 0.65$$

And the suspended sediment load is calculated with the use of the equation below, with SL in tonnes/day and m³/day, Q in m³/s and S_c in mg/l:

$$SL = Q * S_c * 0.0864 \text{ [tonnes/day]} \qquad SL = \frac{Q * S_c * 0.0864}{2.65} \text{ [m}^3\text{/day]}$$

To convert the outcome from tonnes/day to m³/day, a density of 2650 kg/m³, the density of quartz, is assumed for the sediment without pores which is a commonly made assumption for most basins (Bahr et al., 2001). According to Bahr et al. (2001) sediment porosities will typically decrease with depth as overlying sediments compress the underlying material, however due to the shallow character of the former Northern Swamp and the resuspension of the sediments due to the wind and movements of animals this will not be the case. From Bahr et al. (2001) a surface porosity can be derived of approximately 0.6-0.8.

This implies that each m³ of sediment entering through the inlet construction as calculated with the equation presented above that will settle in the former Northern Swamp area, occupies approximately 1.6-1.8 m³.

To provide a better insight in the inflow of water and sediments through the inlet construction into the spillway channel, the inflow is calculated for the year 2010. In order to do this calculation, from the discharge rating curve as presented in Appendix J, is derived that a water height exceeding 6 meters represents a discharge exceeding approximately 60 m³/s.

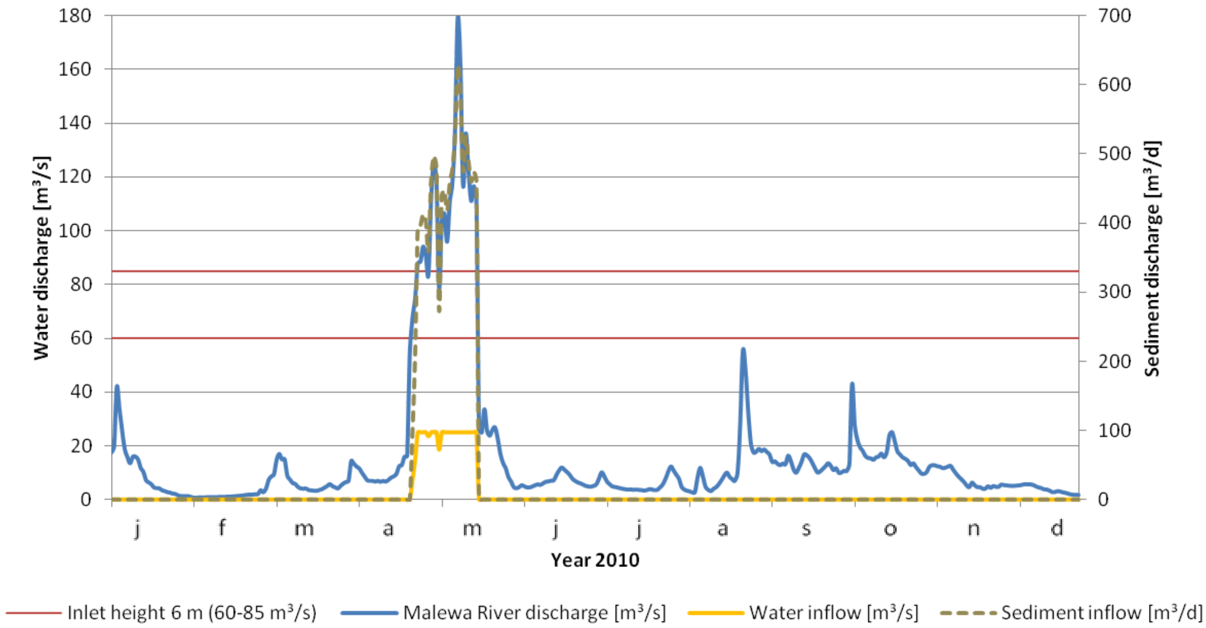


FIGURE 20: YEAR 2010 WATER AND SEDIMENT INFLOW

In Figure 20, the Malewa River discharge at 2GB01 for 2010 is indicated by the blue line, which exceeds a discharge of 60 m³/s from the end of April till halfway May. During this period, water can be diverted into the spillway channel, which is indicated by the yellow line. Yet, the diversion of water into the spillway channel, indicated by the yellow line, needs to be limited to 25 m³/s in order to prevent flooding of the spillway channel. The maximum spillway channel discharge is based on Figure 22 and Figure 23.

Assuming that the level of the base of the inlet construction is going to be constructed at 6 meters above the Malewa River bed, in combination with a discharge exceeding 60 m³/s when the Malewa River water depth reaches 6 meters together with a maximum spillway channel discharge of 25 m³/s results in a 'window of discharge' during which water can be diverted from the Malewa River through the inlet construction into the spillway channel. This 'window of discharge', ranging from 60 to 85 m³/s, is indicated in Figure 20 with the red lines. The sediment inflow entering through the inlet construction is indicated by the grey dotted line. Obviously, sediment inflow only takes place when water inflow can take place, which is during the 'window of discharge'.

The grey dotted line indicating the sediment inflow however, is not flattened like the yellow line indicating the water inflow which can be explained as follows. During higher Malewa River discharges, the sediment concentration S_c increases since: $S_c = a * Q^b$. The sediment concentration thus depends on the Malewa River discharge. The daily suspended sediment load however, depends on the combination of the sediment concentration in the Malewa River water and the diverted discharge through the inlet construction. For example, a water inflow of 15 m³/s contains a sediment concentration of: $S_c = a * Q^b = 26.44 * 75^{0.65}$, since at a water inflow of 15 m³/s the Malewa River discharge is 75 m³/s.

However, a water inflow of 25 m³/s can take place during a Malewa River discharge of 85 m³/s, but also at a Malewa River discharge over 85 m³/s, let's say 100 m³/s. In both cases, the water inflow is 25 m³/s, but the sediment concentration of the water that is diverted from the Malewa River into the spillway channel differs: $S_c = a * Q^b = 26.44 * (60 + 25)^{0.65} = 475\ mg/L$ versus $S_c = a * Q^b = 26.44 * (75 + 25)^{0.65} = 528\ mg/L$.

This relationship between the sediment concentration, the Malewa River discharge and both the water inflow and sediment inflow is further explained for 2010 with the use of Table 4. In this table, the days (column 1) are included in which the Malewa River discharge (column 2) exceeds 60 m³/s. For all of these days, the sediment concentration is calculated (column 3), which, combined with the water inflow through the inlet construction (column 4) leads to the suspended sediment load (column 5).

Adding these numbers leads to a total sediment inflow over 2010, of almost 10900 m³. These sediments will settle, for the wetland alternative, in the former Northern Swamp area and will occupy, when assuming a porosity of 0.6-0.8 (Bahr et al., 2001), over 17400 m³. When assuming the rehabilitated area to comprise approximately 2.5 km² and an evenly spread of the sediments over this area, the sedimentation rate for 2010 would have been between approximately 0.5 and 1 cm.

TABLE 4: YEAR 2010 WATER AND SEDIMENT INFLOW

Date	2GB01 Discharge [m³/s] (Q_{Malewa})	Sediment concentration [mg/l] $S_{c,Malewa} = a * Q_{Malewa}^b$	Water inflow [m³/s] ($Q_{spillway}$)	Suspended sediment load [m³/d] $SL = \frac{Q_{spillway} * S_{c,Malewa} * 0.0864}{2.65}$
24-4	67	408	7	97
25-4	75	437	15	211
26-4	88	485	25	395
27-4	88	487	25	397
28-4	94	507	25	413
29-4	91	495	25	403
30-4	84	469	24	360
1-5	112	567	25	462
2-5	125	610	25	497
3-5	118	588	25	480
4-5	79	451	19	273
5-5	103	539	25	440
6-5	106	549	25	448
7-5	96	513	25	418
8-5	111	563	25	459
9-5	118	588	25	479
10-5	138	651	25	530
11-5	179	770	25	628
12-5	161	719	25	586
13-5	117	583	25	475
14-5	136	644	25	525
15-5	123	602	25	491
16-5	111	565	25	460
17-5	116	583	25	475
18-5	111	566	25	461
		2010 total sediment inflow [m³]		10863
		2010 total sediment inflow compensated for pores [m³]		17381-19553

6.2 SEDIMENT TRANSPORT PROCESSES – SCENARIO 0

In this section, the sediment transport processes are presented and clarified for both the Wetland and Meander alternative for scenario 0: the estimated values for the average grain size and roughness. For the Wetland alternative, which is the most promising alternative concerning the sediment trapping efficacy, the sediment transport processes also for variations in average grain size and roughness, scenario 1a/b and 2a/b, are presented in section 6.3. Table 5 gives an overview of the scenarios with the values used during the "Estimated values" calculations and the "Average grain size variation" and "Roughness variation" calculations.

TABLE 5: SCENARIOS 0, 1 AND 2 WITH PARAMETER VALUES

Scenario	0	1a	1b	2a	2b
	Estimated values	Average grain size variation		Roughness variation	
D50 [mm]	0.22	0.063	1	0.22	0.22
Manning [-]	0.035	0.035	0.035	0.030	0.040

To evaluate the sediment transport processes within the wetland and meander, a maximum discharge of 25 m³/s through the spillway channel is assumed, since this is the discharge at which no flooding takes place, which is defined as constraint in the Wetland rehabilitation project Naivasha - Kenya document (Marula Estates, 2013). For both scenarios, at approximately 25 m³/s the maximum water depth is reached which is a water depth of 1,5 meters at section 1_10, the spillway channel section furthest downstream. The relationship between discharge and water depth in the spillway channel for both alternatives are presented in Figure 22 and Figure 23. The division of the sections over the spillway channel and Wetland/Meander is equal for both alternatives and presented in Figure 21.

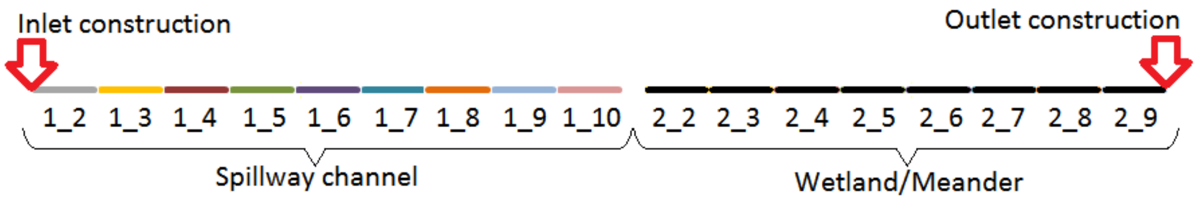


FIGURE 21: SPILLWAY CHANNEL SECTIONS

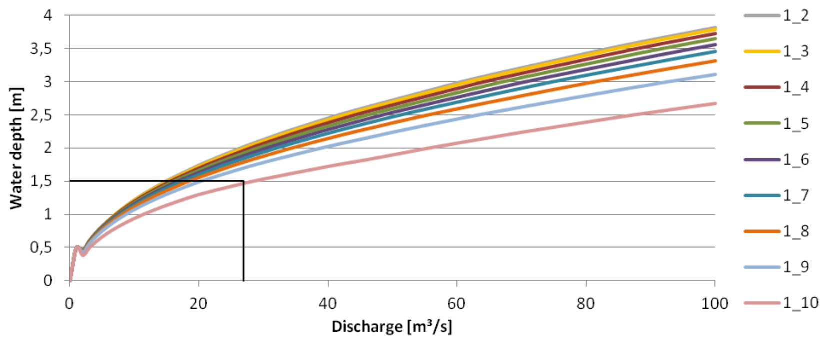


FIGURE 22: WATER DEPTH SPILLWAY CHANNEL - WETLAND ALTERNATIVE

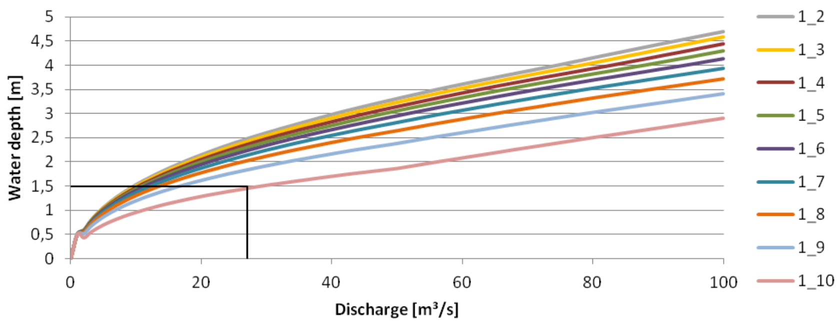


FIGURE 23: WATERDEPTH SPILLWAY CHANNEL - MEANDER ALTERNATIVE

6.2.1 WETLAND ALTERNATIVE

Figure 25 describes the sediment transport processes in the spillway channel and the wetland for the Wetland alternative for the maximum allowed discharge to enter through the inlet construction, which is thus 25 m^3/s. The sediment transport capacity is indicated with the blue line and the flow velocity is indicated with the green line. The water depth is presented only for the spillway channel cross-section and not for the wetland section. This is because the water depth in the wetland itself also depends on infiltration and evaporation and the amount of water already diverted at some point in time, which is not included yet in the model. The sediment inflow is indicated with the red lines, and varies between 395 m^3/d and 628 m^3/d for the year 2010. These values are extracted from Table 4.

The decrease in sediment transport capacity in sections 1_2 till 1_7 can again be explained by the decrease in the flow velocity in section 1_2 till section 1_7. This can be explained with the use of a basic principle: discharge (Q [m^3/s]) equals flow velocity (u [m/s]) times cross-section surface area (A [m]): $Q = u * A$. The discharge is constant, 25 m^3/s. The cross-section surface area increases due to the change in cross-section surface area of the spillway channel, of which the banks becomes less steep. The water depth decreases only slightly, and thus A increases (Figure 24) which results in combination with the constant discharge in a decrease in flow velocity.

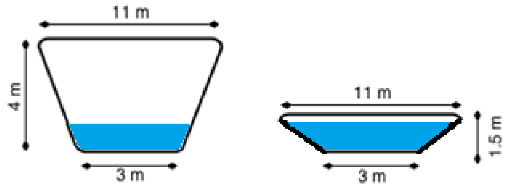


FIGURE 24: CROSS-SECTION INCREASE

The increased sediment transport capacity for section 1_10, 1_9 and 1_8 compared to the sections near the inlet construction, can be explained by the increase in flow velocity, which in its turn causes an increase in shear stress and therefore an increase in sediment transport capacity. The increase in flow velocity is caused by the drop in the water level between the spillway channel and the wetland. This can again be explained with the use of the basic principle: $Q = u * A$. The dramatic increase in cross-section surface area from the spillway channel cross-section to the wetland cross-section leads to a drop in the water level. Therefore the water level in the sections 1_10, 1_9 and 1_8 is lowered and causes an increase in the flow velocity.

In the spillway channel, depending on the Malewa River discharge, the sediment inflow may exceed the sediment transport capacity resulting in sedimentation. The increased sediment transport capacity for the section 1_10, 1_9 and 1_8 may result in erosion of the spillway channel bed and banks. The sediment transport capacity in the wetland is for all sections zero, which results in deposition of all sediments entering the wetland. The sediment transport capacity of zero can again be explained by the low flow velocities.

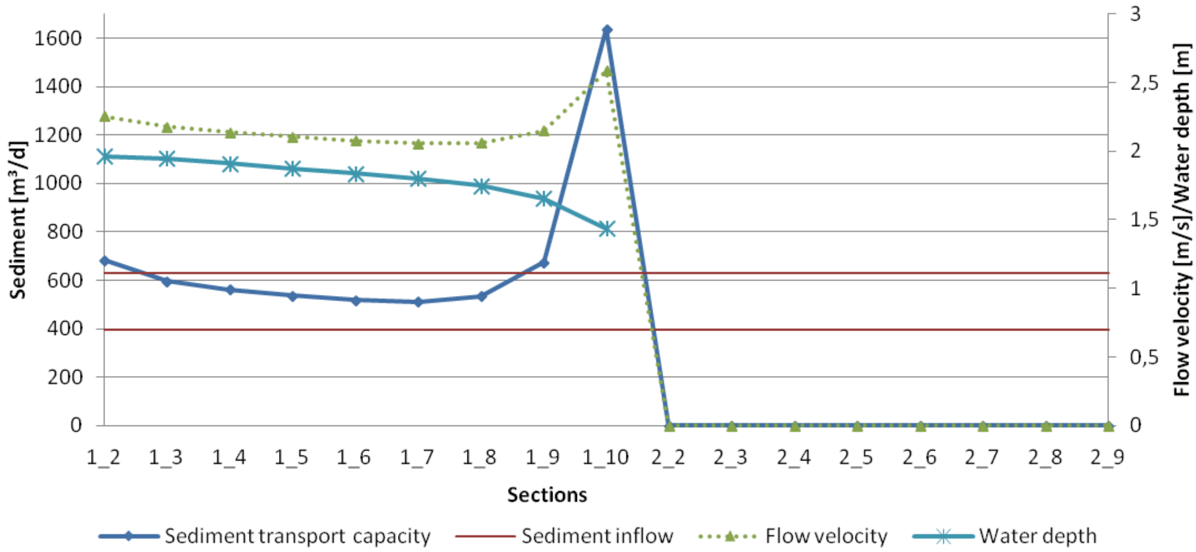


FIGURE 25: SEDIMENT TRANSPORT PROCESSES - WETLAND ALTERNATIVE (Q=25 M³/S)

6.2.2 MEANDER ALTERNATIVE

Again, the sediment transport processes are described for a 25 m³/s inflow, with the sediment inflow varying, depending on the Malewa River discharge, between 395 m³/d and 628 m³/d for the year 2010. As is the case for the Wetland alternative, the increased sediment transport capacity, which is depicted in Figure 26 with the blue line, for sections 1_10, 1_9 and 1_8 compared to the sections near the inlet construction, can again be explained by an increase in flow velocity, which in turn causes an increase in shear stress and therefore an increase in sediment transport capacity.

Only for the section 1_10, 1_9 and 1_8 the sediment transport capacity exceeds the sediment inflow. On sections 1_2 till 1_7, the sediment inflow exceeds the sediment transport capacity, which means sedimentation is going to take place. Also in the meander section, the sediment inflow exceeds the sediment transport capacity which results in the settling of sediments in the channel. This seems promising since the sediments are being trapped, however the sedimentation of the channel will lead to a decrease in the cross-section surface area. This decrease will lead to increased flow velocities, increased sediment transport and further transport of the sediments downstream to the lake. Another possibility is that the decrease in cross-section surface area leads to flooding of the spillway channel and the meander section.

The minor increase in sediment transport capacity in section 2_8 and 2_9 is caused by the increased flow velocity. This increased flow velocity is caused by the downstream boundary condition, which is a water level lower than the water level present in the meander.

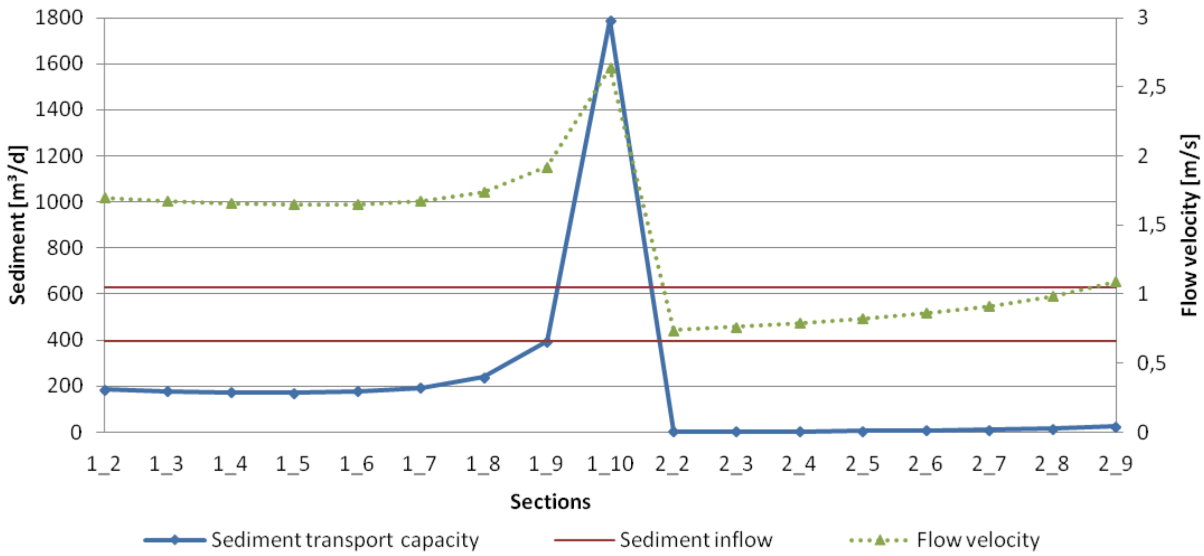


FIGURE 26: SEDIMENT TRANSPORT PROCESSES - MEANDER ALTERNATIVE (Q=25 M³/S)

6.3 WETLAND ALTERNATIVE – SCENARIO 1 & 2

Since the Wetland alternative seems to be most promising considering the sediment trapping efficacy, for this alternative the variation in the results caused by uncertainty in the sediment characteristics and roughness data are investigated for a 25 m³/s discharge on section 1_10, which is the section with the highest sediment transport capacity. The scenarios and the parameter values are presented in Table 5.

6.3.1 SCENARIO 1A & 1B

From Figure 27 it can be noted that the sediment transport capacity decreases considerably for a smaller average grain size (scenario 1a with D50= 0.063 mm) compared to the estimated average grain size (scenario 0 with D50 = 0.22 mm). The sediment transport capacity increases only slightly for a bigger average grain size (scenario 1b with D50 = 1 mm).

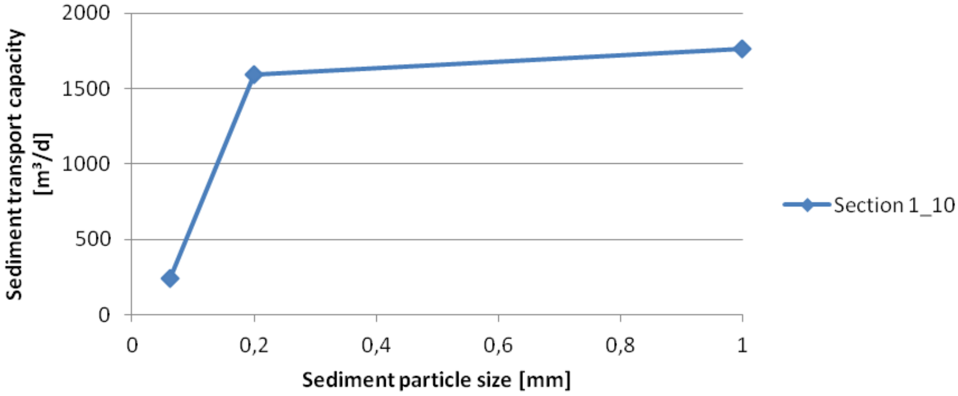


FIGURE 27: VARIATION IN SEDIMENT TRANSPORT CAPACITY DUE TO UNCERTAINTY IN D50 (Q=25 M³/S)

6.3.2 Scenario 2a & 2b

From Figure 28 it can be noted that the sediment transport capacity increases approximately as much as it decreases for respectively a lower (scenario 2a with n = 0.03) and higher (scenario 2b with n = 0.04) hydraulic roughness.

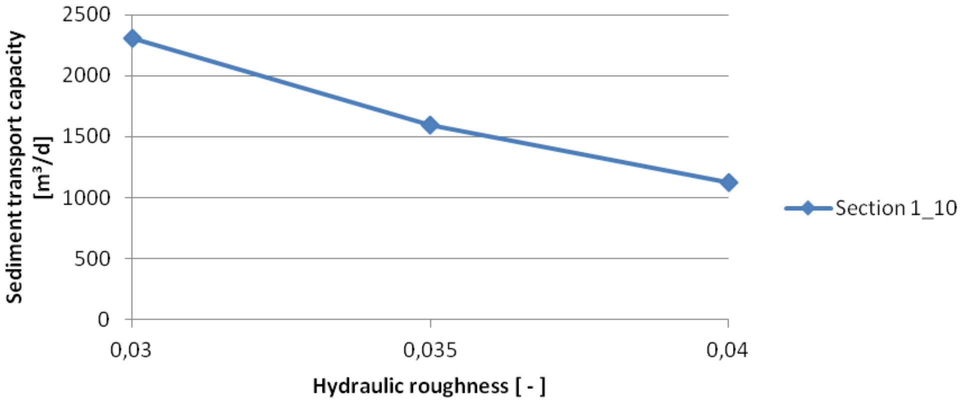


FIGURE 28: VARIATION IN SEDIMENT TRANSPORT CAPACITY DUE TO UNCERTAINTY IN MANNING (Q=25 M³/S)

6.4 Trapping efficacy

In both the Wetland and Meander alternative, sedimentation is going to take place, however the location of where the sedimentation is going to take place differs. In the Wetland alternative, it is difficult to determine whether sedimentation or erosion is going to take place in the spillway channel. The sediment inflow sometimes exceeds, and sometimes deceeds the sediment transport capacity in the spillway channel. Thus sedimentation as well as erosion, depending on the presence and density of vegetation covering the channel bed soil, may take place. There is no sediment transport capacity in the wetland itself, which results in the settling of all sediments entering. In the Meander alternative, sedimentation possibly already takes place in the spillway channel. Only in section 1_10, 1_9 and 1_8 is the sediment inflow exceeded by the sediment transport capacity. For the other sections, the sediment inflow exceeds the sediment transport capacity which will result in sedimentation. The sedimentation will take place until the cross-section surface area decreases to a level where the flow velocity increases again and the sediment transport capacity increases till it exceeds the sediment inflow. These sediments will then be transported further downstream through the spillway channel into the meander. Another possibility is that the decrease in cross-section surface area leads to flooding of the spillway channel. In the meander itself the same processes take place.

In both the Wetland and Meander alternative sedimentation is going to take place, but the trapping efficacy is higher for the Wetland alternative. In this alternative, more sediments can be trapped before the cross-section surface area decreases in such amount that the sediment transport capacity exceeds the sediment inflow again. In the Meander alternative, due to the much smaller cross-section surface area compared to the wetland (Figure 13, SP-C 2 versus WL), sedimentation will cause a quicker decrease in cross-section surface area and therefore an increase in sediment transport capacity.

For the Wetland alternative, for the year 2010 approximately 10800 m³ sediment is diverted through the inlet construction into the wetland where the sediment will settle. To get insight in the reduction of inflow of sediments into Lake Naivasha, as is described as the first goal of the rehabilitation of the former Northern Swamp in the Wetland rehabilitation project Naivasha – Kenya document (Marula Estates, 2013), the inflow of sediments into Lake Naivasha is calculated without any diversion into the wetland. To calculate the total inflow of sediments via the Malewa River, also bed load needs to be included. This is not the case for the water that is diverted through the inlet construction, since only the upper part of the water column, where no bed load transport takes place, is being diverted. The bed load is estimated to be between 5% and 10% of the suspended load according to Lane and Borland (1951)(as cited by Syrén (1990)). In Table 6 the results are presented for this calculation.

What has to be taken into account when interpreting Table 6, is, that to estimate the remaining sediment inflow Lake Naivasha, the assumption is made that the reduced Malewa River discharge after the inlet construction does not influence the sediment transport capacity of the Malewa River downstream of the inlet construction. What most likely is going to happen, is that due to the reduced Malewa River discharge, the sediment transport capacity decreases and sedimentation is going to take place just downstream of the inlet construction. This topic is suggested for further research in section 8.3.

TABLE 6: 2010 SEDIMENT INFLOW INTO LAKE NAIVASHA WITH AND WITHOUT DIVERSION INTO WETLAND

Sediment inflow Lake Naivasha without wetland (suspended + 10% bed load) [m³]	Sediment inflow into wetland, inlet at +6m [m³]	Remaining sediment inflow Lake Naivasha [m³]	Sediment inflow reduction into Lake Naivasha [%]
73930	10863	63067	15

However, measured values reported in the literature indicate that sediment removal efficiencies for wetlands range between 80-90% (Daukus et al., (1989) as cited in Siobhan Fennessy et al. (1994)). For the Naivasha case, this results in the trapping of 80-90% of the sediment entering the wetland: $10863 * (80 - 90\%) = 8690 - 9777\ m^3$. The sediment inflow reduction into Lake Naivasha then reduces to 12-13%.

Another important aspect that needs to be considered is the relatively high Malewa River discharge required for the rehabilitation alternatives to be fed with water. The required minimal discharge of 60 m³/s to exceed a water height of 6 m in the Malewa River, only occurs 1.25% of the time, based on data from 1960 till 2010. In 2010, the Malewa River discharge exceeded 60 m³/s for 25 days, which comes down to almost 7% of the time of the year. Based on the data from 1960 till 2010, the 1.25% resembles approximately 4.5 days per year, and thus the estimated sediment inflow reduction into Lake Naivasha of 15% for the year 2010 is likely to be lower for other years.

CHAPTER 7 – DISCUSSION

In this chapter, processes that not have modeled, but do have an impact on the results, are discussed. These processes will be discussed for the sediment inflow, the spillway channel/meander and the wetland. This chapter concludes with a wrap-up, in which the processes together with impacts are summarized.

7.1 SEDIMENT INFLOW

When considering the relationship between the discharge and the suspended and bed load the aspects that need to be taken into account are the variations in sediment concentration over the water column, the variation in sediment concentration during the rising and falling stage of a peak discharge, the variations in sediment availability over the seasons, and the increased farming activities in the upper-catchment causing an increase in the erosion including the measures to mitigate this increase in erosion.

The variation of the sediment concentration over the water column influences the inflow of sediments through the inlet construction, which of course also depends on the level of the inlet construction. Two forces influencing the sediment concentration over the water column are gravity, bringing the sediments down, and turbulence bringing the sediments up. During peak discharges, due to turbulence the sediments spread over the entire water column and therefore the concentration can be considered to be equal over the water column. During normal discharges however, the flow is less turbulent and therefore the sediments are concentrated in the lower part of the water column. The inflow of sediments thus depends on the level of the inlet construction and the utilization of the wetland. Because of engineering considerations, constructing the base of the inlet construction at a few meters above the river bed of the Malewa River in its river bank is more feasible than constructing the base of the inlet construction at the same level as the river bed. This means for the inlet of water, and thus for the inlet of sediments, that only the upper part of the water column will enter the wetland, which is the part of the water with the lowest sediment concentration. Considering this, the inflow of sediments as presented in Figure 20 will be an over-estimation.

No distinction is made between the variations in sediment concentrations during rising or falling stages of a peak discharge. It is hypothesized, e.g. by Hickin (1995), that during the rising stages of a peak discharge, the sediment concentration is relatively higher compared to the sediment concentration during the falling stage of a peak discharge. This is caused by the relatively high availability of sediments ready to be eroded from within the catchment and the river bed after a dry period. However, for the Naivasha basin relationship between discharge and sediment concentration, the quality of the data makes the use of water stage decomposed samples less valid (Syrén, 1990). The variations in the relationship between discharge and sediment concentrations over the seasons are also not taken into account. Characterizing for the Naivasha basin are the rainy periods April-May and October-November, and the dry periods December-March and June-September. This may cause differences in the sediment availability over the seasons; however samples of sediment concentration and discharge are not significantly different from each other. From this it can be concluded that characteristics of rainfall, soil erodibility and transport are similar irrespective of the season (Syrén, 1990). Therefore, seasonal decomposition is not included in the relationship between discharge and sediment transport.

What influences the amount of sediments available for transport, are the increased farming activities in the catchment which lead to an increase in erosion (Becht et al., 2005; Harper et al., 2005; Everard et al., 2002). Since the late nineties, the sedimentation rate in the lake has increased from approximately 0.5 cm per year (Rupasingha, 2002) up to over 1 cm per year in 2006 (Stoof-Leichsenring et al., 2011) showing an upward shift in the relationship between discharge and sediment concentration. To mitigate the increased erosion and the related problems, mitigating measures are being undertaken in the catchment, but it is not possible yet to accurately quantify the impacts of these measures (Chiramba et al., 2011). For now, since the increase in farming activities is a process already taking place for several years and the implementation of mitigating measures just started recently, it can be assumed that the relationship between discharge and sediment concentration presented by Syrén (1990) is the minimum and is likely to be higher, resulting in higher amounts of sediment inflow as compared to the results as presented in Figure 20. However, also erosion mitigating measures are taken upstream in a 'Payment for Environmental Services' pilot project by a WWF-Care-Kenya partnership in 2011, such as the establishment of grass strips/terraces to reduce runoff and erosion on steep slopes in the Wanjohi and Turasha sub-basins of the Malewa River basin. Significant land and water management improvements have been accomplished, but the results of these measures are not accurately quantified yet (Chiramba et al., 2011). These measures will, to some extent, nullify the increased erosion caused by the increased farming activities.

7.2 Spillway channel / Meander

Prone to the discussion concerning the sediment transport processes in the spillway channel is the sediment available for transport. The calculated sediment transport capacity is the amount of sediment that in theory can be transported given the flow velocity and hydraulic parameters such as the discharge and the spillway channel dimensions. In this case, it is assumed that only sediments are being transported from the Malewa River that enter the spillway channel via the inlet construction. Sediments that are not being accounted for are those that erode from the spillway channel banks or bed. This assumption is maybe true when the spillway channel and banks are densely vegetated, and this vegetation is able to prevent the banks and bed to erode. Vegetation increases the flow resistance and reduces the shear stress exerted on the river bed and banks. This results in reduced capacity of bed-load transport and increased capacity for trapping, deposition and stabilization of sediment (Wu et al., 2009). The presence and density of vegetation is affected by the occurrence of extreme events such as floods or droughts and by grazing and trampling by animals.

High flow velocities and turbulent flows during flood events can cause damage to the vegetation and its roots, tearing apart the layer of vegetation that formed an armored layer over the spillway channel banks and bed. The absence of such armored layer leads to erosion of the soils underneath, increasing the amount of sediment available for transport, which eventually end up downstream. Also due to prolonged droughts vegetation loses its ability to prevent erosion. Prolonged droughts cause the vegetation, including its roots, to die, which used to hold together the soils forming this armored layer. When, after the drought, water starts flowing again through the spillway channel the dead vegetation cannot function as an armored layer anymore.

The former Northern Swamp is densely populated by animals such as hippos and water buffaloes, which affect the presence of vegetation by their grazing and trampling. Grazing causes the river banks to lose its capacity to trap sediments originating from sheet erosion. Trampling causes damage to the armored layer resulting in increased sediment transport as described in the previous section. The impact of their presence on the vegetation can be seen in Figure 29.

FIGURE 29: RIVER BANK EROSION CAUSED BY ANIMALS

Given these facts, the occurrence of extreme events and the presence of animals, it can be assumed that erosion is going to take place in the spillway channel and, when taking into account the sediment transport capacity high enough to transport these newly eroded sediments, will lead to an increased sediment load entering the wetland.

7.3 WETLAND

Issues that need to be discussed concerning the sediment transport processes in the wetland are the schematization of the wetland in the SOBEK-model, the wetland bottom morphology, resuspension of sediments from the wetland bottom and the trapping of sediments in front of the outlet construction.

The schematization of the wetland in the SOBEK-model, in particular the changeover between spillway channel and wetland, is just a very simple approximation of the wetland as it will be constructed. Where in the model there is a sharp changeover from the spillway channel cross-section to the wetland cross-section, in reality most likely a delta will be formed by the deposition of sediments. Depending on the utilization of the wetland, the delta morphology will be river (spillway-channel) or wave-dominated. During relatively low spillway-channel discharges, waves can influence the delta formation, while during relatively high spillway-discharges the delta formation will be dominated by discharge and the accompanying high flow velocities and high sediment concentration. Sediment deposited near the outlet of the spillway channel in the wetland, are likely to be transported over the wetland by wave-induced resuspension, comparable to the sediment dynamics in Lake Naivasha itself (Tarras-Wahlberg et al., 2002). Considering the wetland bottom itself, in reality, compared to the flat wetland bottom as schematized in the SOBEK-model, the wetland bottom will be characterized by small islands with channels flowing in between them. Because of the variations in discharge, sediment transport caused by wind-induced resuspension and the presence of animals, this system of islands and channels will be dynamic. These dynamics will most likely increase the sediment transport capacity. The quantification of the impacts on the sediment transport capacity caused by the dynamic system is outside the scope of this research, but given these processes it is likely that the sediment transport capacity in the wetland as presented in Figure 25 is an under-estimation.

As stated in the previous section, processes causing the sediments to resuspend from the wetland bottom are the wind and the movements of animals in the wetland. The occurrence of wind-induced resuspension depends on the fetch, which is the distance of water over which the wind can blow, the water depth and the bottom material characteristics. Wind energy transforms into waves, currents and turbulence in the water column, leading to erosion of bottom material when the bottom shear stress exceeds the critical bottom shear stress (Evans, 1994). Due to the low water depth, even for low wind speeds the wind energy is likely to be able to be transformed into sufficient bottom shear stress to mobilize sediment. Especially near the entrance of the spillway-channel in the wetland, where the sediments are begin deposited and the water depth is lowest, the bottom shear stress can exceed the critical bottom shear stress and lead to resuspension. Again supporting the idea as expressed in the previous section that the sediment transport capacity in the wetland as presented in Figure 25 is an under-estimation.

The movements of animals, and in particular mammals such as water buffaloes and hippos, cause erosion at the banks of the small islands in the wetland and resuspension of the sediments deposited on the wetland bottom. Both processes of erosion caused by mammals, as well as resuspension were observed during a field visit to the already functioning Gilgil Wetland and are depicted in Figure 30 and Figure 31. Also the movement of animals supports the idea that the sediment transport capacity in the wetland as presented in Figure 25 is an under-estimation.

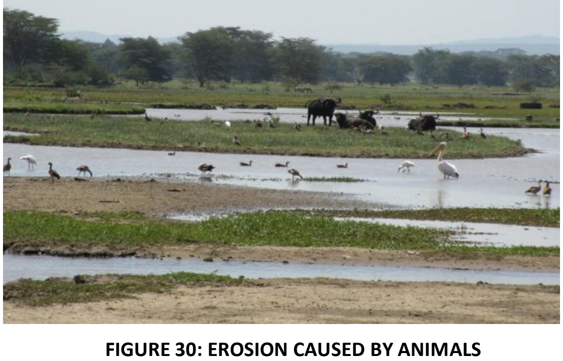


FIGURE 30: EROSION CAUSED BY ANIMALS

FIGURE 31: RESUSPENSION CAUSED BY HIPPO'S

The outlet construction, consisting of a concrete wall of approximately 1 m high and 30 m wide, forms an obstacle in the flow causing only the top layer of the water column to flow further. As explained in the first section of this chapter, the sediment concentration decreases from the bottom of the water layer to the top. This causes water with a relatively low sediment concentration to flow into the lake and the water with a relatively high sediment concentration gets buffered in front of the outlet construction. These sediments will settle and accumulate in front of the spillway channel.

7.4 DISCUSSION WRAP-UP

The processes mentioned in this chapter all have their impacts on the results, causing the results either to be under or over-estimated, or the impact cannot be determined. The processes including the impacts are summarized in Table 7.

TABLE 7: PROCESSES INCLUDING IMPACT ON RESULTS

Process	Cause results to be		
	Under-estimated	Unable to define	Over-estimated
Sediment inflow			
Vertical distribution sediment concentration			x
Temporal sediment load variation		x	
Increased farming activities not included	x		
Spillway channel/meander sediment transport			
Bank erosion	x		
Wetland sediment transport			
Wind-induced resuspension	x		
Movements by animals	x		
Presence of the outlet construction		x	

CHAPTER 8 – CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the conclusions of this research are presented, together with recommendations addressed to WRMA and Marula Estates to improve this research and suggestions for further research to improve the understanding about the rehabilitation of the former Northern Swamp.

8.1 CONCLUSIONS

This chapter presents the conclusions of this research, and this is done based on the research objective:

To evaluate the functioning of two alternative rehabilitation alternatives, with in particular the sediment trapping efficacy, by modeling the sediment inflow for various Malewa River discharges using a one-dimensional modeling approach

To reflect on this research objective, the conclusions on the two main research questions are presented separately in the next sections. In section 8.1.1 the conclusion on research question 1 is presented and in section 8.1.2 the conclusion on research question 2.

1. *What is the most promising rehabilitation alternative, in particular concerning the sediment trapping efficacy?*
2. *What is the reliability of the one-dimensional modeling approach?*

8.1.1 PREFERRED ALTERNATIVE

Of the two evaluated rehabilitation alternatives, the Wetland alternative and the Meander alternative, the Wetland alternative turns out to be the most promising when considering the sediment trapping efficacy. With this alternative, for the year 2010 a reduction of 15% of the inflow of sediment into Lake Naivasha could have been established when this measure would have been implemented (Table 8).

TABLE 8: 2010 SEDIMENT INFLOW INTO LAKE NAIVASHA WITH AND WITHOUT DIVERSION INTO WETLAND

Sediment inflow Lake Naivasha without wetland (suspended + 10% bed load) [m³]	Sediment inflow into wetland, inlet at +6m [m³]	Remaining sediment inflow Lake Naivasha [m³]	Sediment inflow reduction into Lake Naivasha [%]
73930	10863	63067	15

Based on the method used in this research, the sediment transport capacity, approximately 10863 m³ of sediment would have settled in 2010. However, measured values reported in the literature indicate that sediment removal efficiencies for wetlands range between 80-90% (Daukus et al., (1989) as cited in Siobhan Fennessy et al. (1994)). For the Naivasha case, this results in the trapping of 80-90% of the sediment entering the wetland: $10863 * (80 - 90\%) = 8690 - 9777\ m^3$. The sediment inflow reduction into Lake Naivasha then reduces to 12-13%.

For both alternatives, re-establishment of the former Northern Swamp, the main objective of the Wetland rehabilitation project, is still going to be difficult to accomplish. Only during relatively high discharges, discharges exceeding 60 m^3/s, which occur approximately 1.25% of the time based on data from 1960 till 2010, water is able to enter through the inlet construction. It is therefore going to be difficult to keep the wetland area inundated in order to re-establish the former Northern Swamp. Also, in 2010 the Malewa River discharge exceeded a discharge of 60 m^3/s 25 days, which is almost 7% of the time. The 1.25% resembles approximately 4.5 days per year, and thus the estimated sediment inflow reduction into Lake Naivasha of 15% for the year 2010 is likely to be lower for other years.

What favors the Meander alternative becomes clear when also the other objectives of the rehabilitation plan, as described in the Wetland rehabilitation project Naivasha – Kenya document (Marula Estates, 2013), are taken into account (Table 1). Its major advantage compared to the Wetland alternative is its natural character due to the absence of hard structures such as the outlet construction. The absence of these hard structures gives the meander the freedom to change its course over time and diverge in a dendritic pattern as used to be the case in the late seventies (Gaudet, 1979).

8.1.2 Model reliability

For this research, a one-dimensional model was developed in SOBEK to describe the sediment transport processes for various discharges and thus to determine the sediment trapping efficacy for the two rehabilitation alternatives. With this model it is possible to make an estimation of the amounts of sediments entering through the inlet construction, and is it possible to get insight in the sediment transport processes within the two rehabilitation alternatives. The simulations with scenario 1a & 1b and 2a & 2b for the Wetland alternative prove that the modeled sedimentation processes are valid for a range of the input values average grain size and hydraulic roughness. The real absolute numbers of sediment inflow and transport may differ from the modeled numbers, however the estimated reduced sediment inflow into Lake Naivasha of 15% in 2010 is a reasonable estimate.

Although no calibration or validation of the model was possible, it can be concluded that this model has much more potential by firstly improving the availability and quality of the necessary data which makes it possible to reduce the amount of assumptions that had to be made, and secondly by detailing the model to improve its real word resemblance, by including more processes such as wind driven resuspension.

At the moment of developing this model, several aspects of the design are not specified yet such as the level of the inlet construction, but the most important not yet specified aspect is the management of the inlet construction which is going to determine the amount of water, including sediments, going to flow in the water system. Also the quality of the data characterizing the former Northern Swamp, not related to the design specifications, such as sediment particle size and vegetation presence and density determining hydraulic roughness can be improved. Aspects not taken into account in this model, but of which the impacts on the sediment transport processes are considered to be considerable are resuspension caused by the movements of animals and wind-driven resuspension. Including these processes will improve the model validity.

8.2 Recommendations

This section provides recommendations, directed to WRMA and Marula Estates, to improve the results and the use of the results of this research. Recommendations addressed to WRMA are:

1. To develop a rating curve for the spillway channel and the Malewa River near inlet construction;
   This way it becomes possible to estimate the discharge through the inlet construction based on the water depth and with this the sediment trapping efficacy. When the sediment trapping efficacy is known, Marula Estates is able to prepare for example maintenance schemes to dredge the wetland.

2. To determine suspended sediment concentration and particle size distribution for the Malewa River sediments;
   This is to decrease the uncertainty in suspended sediment load in the Malewa River and the sediment transport capacity caused by average grain size variation.

Recommendations addressed to Marula Estates are:

1. To reconsider the necessity of the inlet construction;
   The construction of the inlet construction is going to be a costly operation, and when constructed its stability is going to be endangered by erosion taking place around this concrete structure. Utilization of the inlet construction will also be occurring just sporadically, given the high discharge needed to reach the required water height and therefore the necessity of four sluice gates can be questioned. A cheaper and more natural solution could be to construct a fixed earth weir over which the water will flow when the water depth in the Malewa River reaches 6 m. A drawback of this fixed earth weir, is that the inflow into the spillway channel cannot be limited which may result in flooding. The advice is to weigh the costs of a possible flooding versus the costs of the construction of a, most likely soon to be instable, concrete inlet construction.
2. To relocate the location of the inlet construction and the spillway channel course;
   This relocation makes it possible to improve the use of the designated area by implementation of the wetland design turning out to be most effective. By shifting the spillway channel northwards, a larger area becomes available for sediments to settle.
3. To improve the design with in particular the inlet construction;
   At the location where the inlet construction is going to be constructed proposed by Marula Estates, and also at the location proposed in section 3.1, the Malewa River bed has eroded to approximately 10 m below ground level. When constructing a 5 m high concrete structure in this deep and also steep river bank, measures to ensure the stability of the structure have to be taken. The inlet construction is going to be constructed in the outer bend of the Malewa River, which is most vulnerable to erosion (Knighton, 1998) and therefore the stability of the structure will be in jeopardy. Since the rehabilitation project takes place in a natural environment, measures are suggested that fit in this environment. Guidelines, such as McCullah et al. (2005) and Scottish Environment Protection Agency (2008) on how to implement these measures and how and why to choose for a certain measure, can be of help.
4. To develop a management plan for the inlet construction for regulating inflow to the wetland;
   The inlet construction consists of 4 gates that can be controlled independently. Based on the discharge, and the corresponding water depth, and the regulation of the 4 gates in the inlet construction, water can be diverted from the Malewa River to the former Northern Swamp. The regulation of the inlet construction is going to determine the sediment trapping efficacy of the rehabilitation plan, but is also going to influence the Malewa River section downstream of the inlet construction. Therefore it is important to know, also for WRMA since they are the institution responsible for the management of the Malewa River and Lake Naivasha, how the inlet construction is going to be regulated.

A recommendation that seems to be straightforward, but of which the importance should not be under-estimated, is to sustain or even improve the relationship between WRMA and Marula Estates. This rehabilitation project is initiated to contribute to the sustainable management of the lake; however, the management of the water in the Lake Naivasha basin is prone to discussion. Therefore it should be prevented that this measure is going to lead to discussion by close cooperation between WRMA and Marula Estates, but also other stakeholders affected by this rehabilitation project.

8.3 Further research

In this section, suggestions for further research are done to improve the understanding of the impacts of the rehabilitation project on the former Northern Swamp, but also on the Malewa River and Lake Naivasha. To get better insight in the sediment trapping efficacy of the Wetland alternative, research on wind-driven resuspension and the movement of animals can be of contribution. As already stated in Chapter 7, these two processes cause resuspension and therefore will decrease the sediment trapping efficacy. By quantifying the impact of these processes on the sediment trapping efficacy, the impact of the rehabilitation project can be understood better.

To get better insight in when maintenance is going to be necessary in the Wetland alternative, a detailed elevation map of the former Northern Swamp needs to be established. Based on this map and the estimated discharges entering through the inlet construction, an estimate can be made about the sedimentation rate and locations within the former Northern Swamp.

Other processes going to take place, mainly in the Wetland alternative, are evaporation and infiltration. These processes are expected to be negligible for the Meander alternative compared to the Wetland alternative, however, further research has to prove this guess. An inversed auger-hole infiltration test was done as part of the field work for this research. The results of the test are included in this report in Appendix L.

The divergence of water into the spillway channel is also going to have impacts on the section of the Malewa River downstream of the inlet construction. What is expected to happen, but what should be confirmed by further research, is that due to the lowered discharge, the flow velocity will decrease and therefore sedimentation is going to take place. To support this further research, measurements have already been done on the Malewa River cross-section with the use of an Acoustic Doppler Current Profiler, and an estimation of the river bed slope is determined based on a Digital Elevation Model and Google Earth. The results of these measurements are included in this report in Appendix H and Appendix M.

LITERATURE

Bahr, D. B., Hutton, E. W. H., Syvitski, J. P. M., & Pratson, L. F. (2001). Exponential approximations to compacted sediment porosity profiles. *Computers & Geosciences, 27*(6), 691-700. doi: http://dx.doi.org/10.1016/S0098-3004(00)00140-0

Becht, R., Odada, E. O., & Higgins, S. (2005). Lake Naivasha : experience and lessons learned brief. *In: Lake basin management initiative : Experience and lessons learned briefs. including the final report: Managing lakes and basins for sustainable use, a report for lake basin managers and stakeholders. Kusatsu : International Lake Environment Committe Foundation (ILEC), 2005. pp. 277-298*.

Bolla Pittaluga, M., Nobile, G., & Seminara, G. (2009). A nonlinear model for river meandering. *Water Resources Research, 45*(4), W04432. doi: 10.1029/2008wr007298

Bukaveckas, P. A. (2007). Effects of Channel Restoration on Water Velocity, Transient Storage, and Nutrient Uptake in a Channelized Stream†. *Environmental Science & Technology, 41*(5), 1570-1576. doi: 10.1021/es061618x

Chiramba, T., Mogoi, S., Martinez, I., & Jones, T. (2011). *Payment for Environmental Services pilot project in Lake Naivasha basin, Kenya - a viable mechanism for watershed services that delivers sustainable natural resource management and improved livelihoods*. Paper presented at the Water in the green economy practice: Towards Rio+20, Zaragoza, Spain.

Chow, V. T. (1959). *Open-Channel Hydraulics*. Illinois: University of Illinois.

Cornelissen, M. A. J. M. (2013). *Wetland optimization; Literature review*. Literature study. University of Twente. Enschede.

Deltares. (2011). SOBEK (Version 2.12.002a). Delft: Deltares.

Evans, R. D. (1994). Empirical evidence of the importance of sediment resuspension in lakes. *Hydrobiologia, 284*(1), 5-12. doi: 10.1007/bf00005727

Everard, M., Vale, J., Harper, D., & Tarras-Wahlberg, H. (2002). The physical attributes of the Lake Naivasha catchment rivers. *Hydrobiologia, 488*(1-3), 13-25. doi: 10.1023/a:1023349724553

Fisher, J., & Acreman, M. (1999). Wetland nutrient removal: a review of the evidence. *Hydrology and Earth System Sciences, 8*(4), 673-685.

Gaudet, J. J. (1979). Seasonal Changes in Nutrients in a Tropical Swamp: North Swamp, Lake Naivasha, Kenya. *Journal of Ecology, 67*(3), 953-981. doi: 10.2307/2259223

Girma, A., Rossiter, D. G., Siderius, W., & Hennemann, G. R. (2001). Soils of the lake Naivasha area, Kenya : summary of the investigations 1997 - 2000 by the Soil Science Division of ITC (pp. 32 p.). Enschede: ITC, Soil Science Division.

Gitonga, M. S. (1999). *Study of long term waterbalance of Lake Naivasha, Kenya.* Enschede, The Netherlands.

Gumbel, E. J. (1941). The Return Period of Flood Flows. (2), 163-190. doi: 10.1214/aoms/1177731747

Harper, D., & Mavuti, K. (2004). Lake Naivasha, Kenya: Ecohydrology to guide the management of a tropical protected area. *International Journal of Ecohydrology & Hydrobiology, 4*(3), 287-305.

Harper, D., & Zalewski, M. (1999). *Ecohydrology: Science and the sustainable management of tropical waters.* Paper presented at the Ecohydrology: Science and the sustainable management of tropical waters, Paris.

Harper, D. M., Morrison, E. H. J., Macharia, M. M., Mavuti, K. M., & Upton, C. (2011). Lake Naivasha, Kenya: ecology, society and future. *Freshwater Reviews, 4*(2), 89-114.

Hickin, E. J. (1995). *River geomorphology*: Wiley.

Kitaka, N., Harper, D., Mavuti, K., & Pacini, N. (2002). Chemical characteristics, with particular reference to phosphorus, of the rivers draining into Lake Naivasha, Kenya. *Hydrobiologia, 488*(1-3), 57-71. doi: 10.1023/a:1023353825462

Knighton, D. (1998). *Fluvial Forms and Processes: A New Perspective*. London: Hodder Education.

Lancaster, S. T., & Bras, R. L. (2002). A simple model of river meandering and its comparison to natural channels. *Hydrological Processes, 16*(1), 1-26. doi: 10.1002/hyp.273

Levinson, A. A. (1974). *Introduction to exploration geochemistry. [Textbook].*

Loucks, D. P., & Van Beek, E. (2005). *Water Resources Systems Planning and Management; An Introduction to Methods, Models and Applications*. Delft: WL | Delft Hydraulics.

Lukman, A. P. (2003). Regional impact of climate change and variability on water resources; Case study Lake Naivasha Basin, Kenya. Enschede: International Institute for Geo-Information Science and Earth Observation.

Marula Estates (Producer). (2009). Lake Naivasha Wetland Rehabilitation Project Northern Swamp regeneration.

Marula Estates. (2013). Wetland Rehabilitation Project Naivasha - Kenya; Second Phase - Weir A. Naivasha.

McCullah, J., & Gray, D. H. (2005). *Environmentally sensitive channel-and bank-protection measures* (Vol. 544): Transportation Research Board.

Meins, F. M. (2013). *Evaluation of spatial scale alternatives for hydrological modelling of the Lake Naivasha Basin, Kenya.* (Masters), University of Twente, Enschede.

Morris, G. L., & Fan, J. (1998). *Reservoir Sedimentation Handbook*: McGraw-Hill.

Morrison, E., & Harper, D. (2009). Ecohydrological principles to underpin the restoration of <i>Cyperus papyrus at Lake Naivasha, Kenya. *Ecohydrology & Hydrobiology, 9*(1), 83-97. doi: 10.2478/v10104-009-0036-6

Ndungu, J., Monger, B. C., Augustijn, D. C. M., Hulscher, S. J. M. H., Kitaka, N., & Mathooko, J. M. (2013). Evaluation of spatio-temporal variations in chlorophyll-a in Lake Naivasha, Kenya: remote-sensing approach. *International Journal of Remote Sensing, 34*(22), 8142-8155. doi: 10.1080/01431161.2013.833359

Oosterbaan, R. J. N., H.J. (1994). Determining the saturated hydraulic conductivity *Drainage principles and applications*. Wageningen: ILRI.

Ramsar. (1971). Convention on Wetlands of international importance especially as waterfowl habitat. Iran: Ramsar.

Reta, G. L. (2011). *Groundwater and lake water balance of Lake Naivasha using 3-D transient groundwater model.* (Masters), University of Twente, Enschede.

Rupasingha, R. A. P. (2002). *Use of GIS and RS for assessing lake sedimentation processes : case study for Naivasha Lake, Kenya.* ITC, Enschede.

Scottish Environment Protection Agency. (2008). Engineering in the Water Environment Good Practive Guide; Bank protection: Rivers and Lochs.

Siderius, W., & Urassa, G. J. (1999). Wetland soils of lake Naivasha, Kenya. *In: Shallow tropical waters and humans : an international conference, Naivasha Kenya, April 11-16th 1999. 2 p.*

Siobhan Fennessy, M., Brueske, C. C., & Mitsch, W. J. (1994). Sediment deposition patterns in restored freshwater wetlands using sediment traps. *Ecological Engineering, 3*(4), 409-428. doi: http://dx.doi.org/10.1016/0925-8574(94)00010-7

Stoof-Leichsenring, K., Junginger, A., Olaka, L., Tiedemann, R., & Trauth, M. (2011). Environmental variability in Lake Naivasha, Kenya, over the last two centuries. *Journal of Paleolimnology, 45*(3), 353-367. doi: 10.1007/s10933-011-9502-4

Syrén, P. (1990). Estimated Transport of the Suspended Load of the River Malewa, Kenya, between 1931-1959. *Geografiska Annaler. Series A, Physical Geography, 72*(3/4), 285-299. doi: 10.2307/521156

Tarras-Wahlberg, H., Everard, M., & Harper, D. (2002). Geochemical and physical characteristics of river and lake sediments at Naivasha, Kenya. *Hydrobiologia, 488*(1-3), 27-41. doi: 10.1023/a:1023301808624

Teledyne RD Instruments. (2011). Acoustic Doppler Current Profiler. United States: Teledyne RD Instruments.

van Rijn, L. (1984). Sediment Transport, Part I: Bed Load Transport. *Journal of Hydraulic Engineering, 110*(10), 1431-1456. doi: doi:10.1061/(ASCE)0733-9429(1984)110:10(1431)

Vymazal, J. (2007). Removal of nutrients in various types of constructed wetlands. *Science of The Total Environment, 380*(1–3), 48-65. doi: http://dx.doi.org/10.1016/j.scitotenv.2006.09.014

Water Resources Management Authority. (2010). Water Allocation Plan - Naivasha Basin 2010-2012. Naivasha.

Willy, D. K., Kuhn, A., & Holm-Mueller, K. (2012). Payments for Environmental Services (PES) and the Characteristics of Social Ecological Systems: the Case of Lake Naivasha Basin.

WorldRiskReport. (2012). World Risk Report: Environmental degradation and disasters. Brussels.

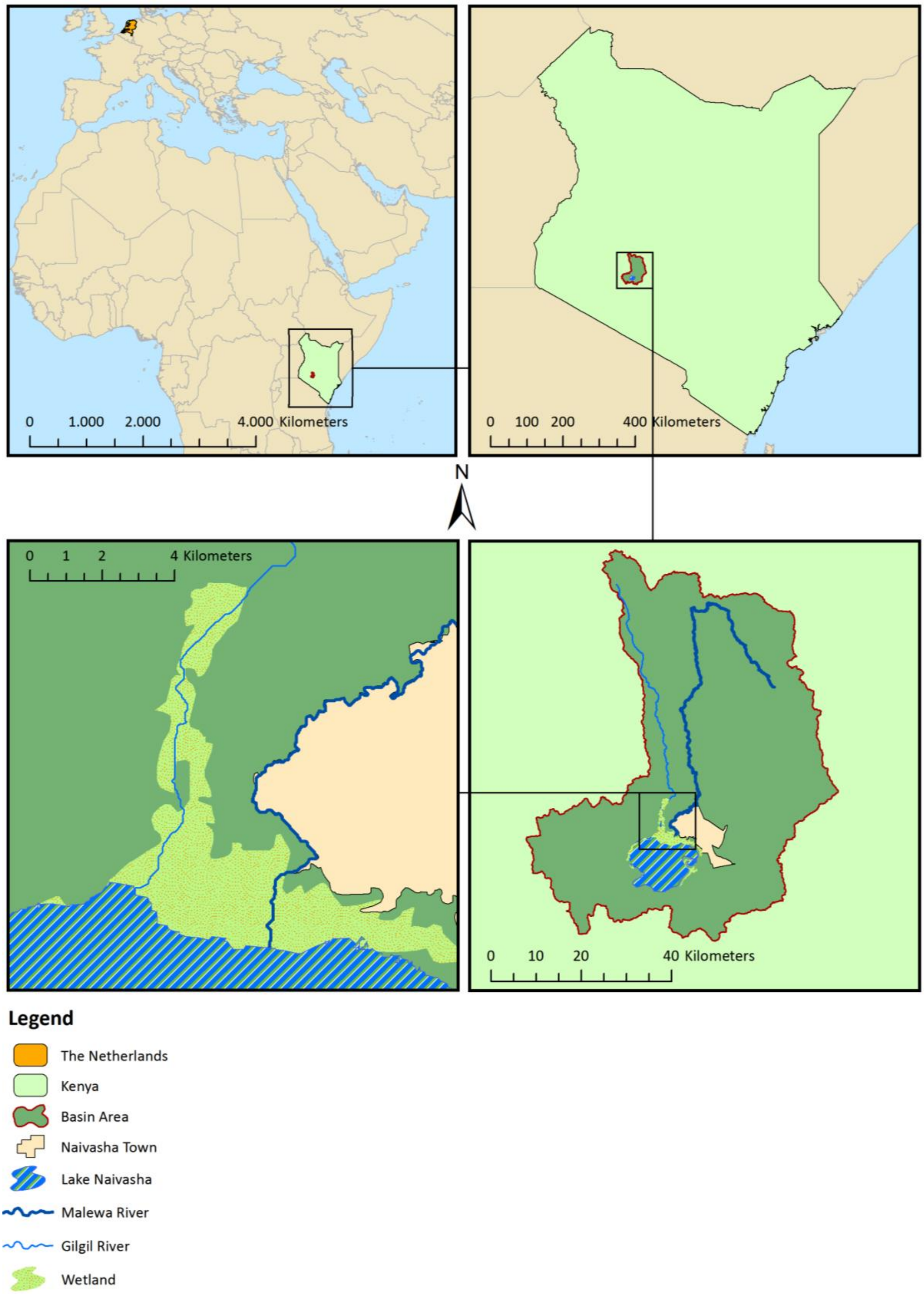
WRMA. (2013). Water Resources Management Authority Retrieved 2014-02-06, 2014, from http://www.wrma.or.ke/index.php/about-us/vision-mission.html

Wu, W., & He, Z. (2009). Effects of vegetation on flow conveyance and sediment transport capacity. *International Journal of Sediment Research, 24*(3), 247-259. doi: http://dx.doi.org/10.1016/S1001-6279(10)60001-7

APPENDICES

Appendix A - Overview location Lake Naivasha

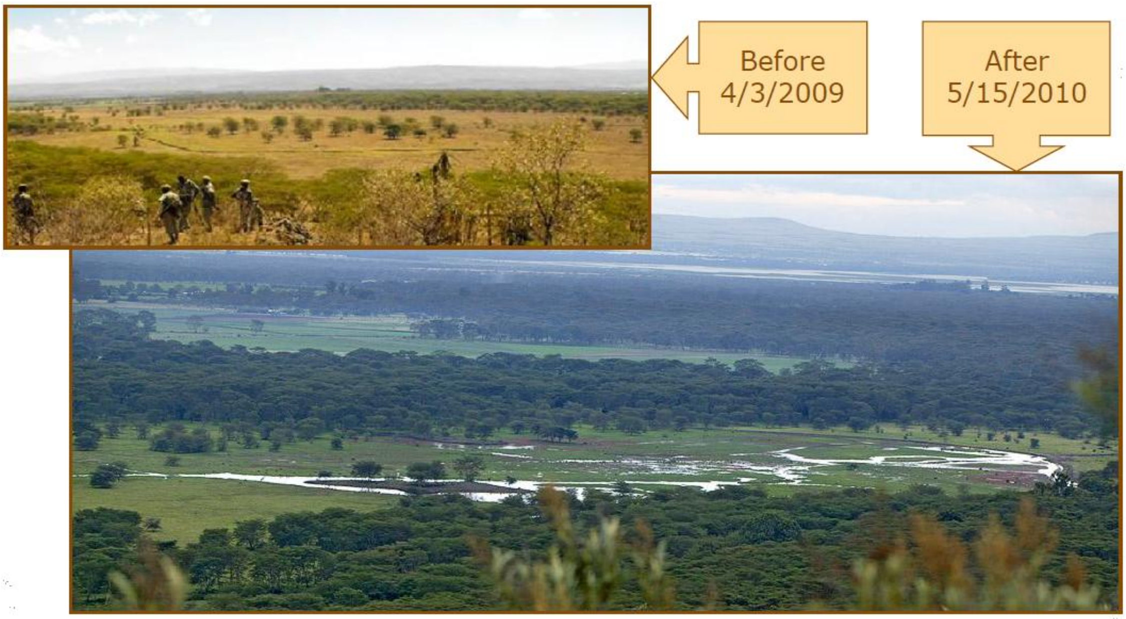
Overview of the location of Lake Naivasha, including the former Northern Swamp and the inflowing Malewa and Gilgil River.



APPENDIX FIGURE 1: LOCATION LAKE NAIVASHA

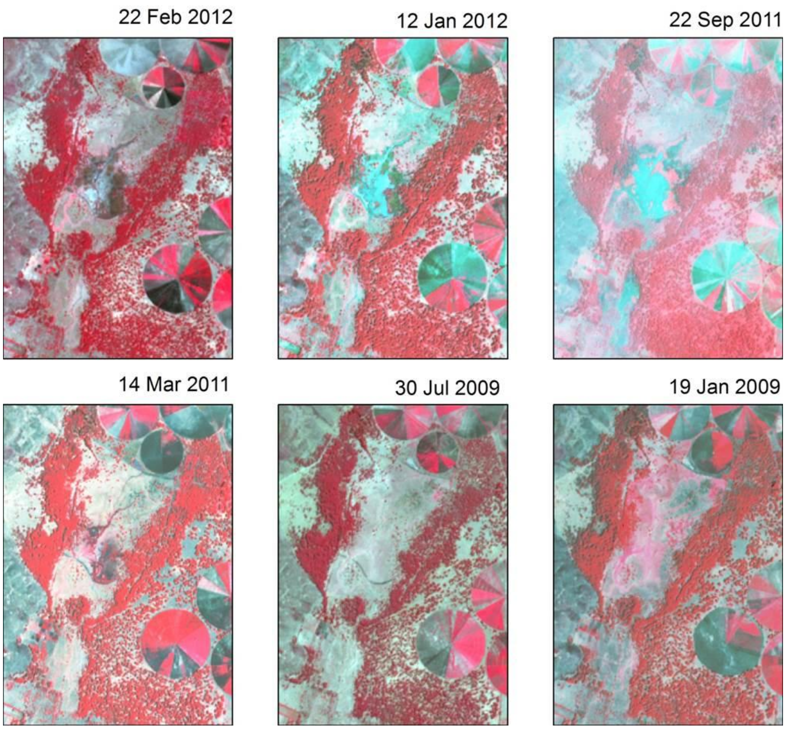
Appendix B - Lake Naivasha Wetland Restoration Project: Phase I Results

The results of phase I of the Lake Naivasha Wetland Restoration Project by Marula Estates: the wetland created in the northern part of the former Northern Swamp fed by the Gilgil River (image source: Marula Estates (2009)).



APPENDIX FIGURE 2: RESULTS GILGIL RIVER WETLAND

Also with the use of satellite images the emerging wetland can be visualized. This image must be viewed from right to left, starting from the lower right. In January 2009, no rehabilitation actions had been undertaken yet, while in July 2009 the dike is constructed. From that period on, behind this dike a wetland has emerged in the northern part of the former Northern Swamp fed by the Gilgil River.

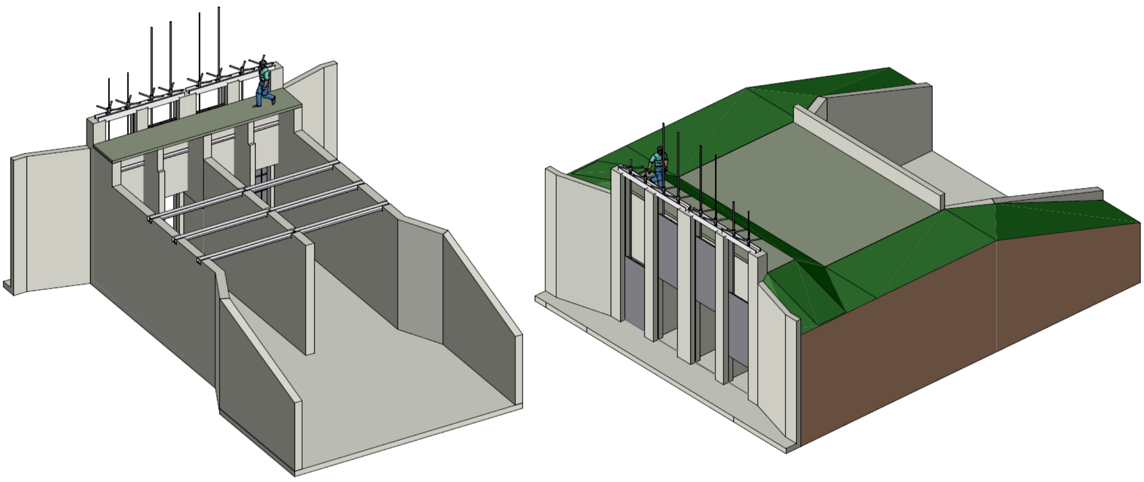


APPENDIX FIGURE 3: EMERGING GILGIL RIVER WETLAND

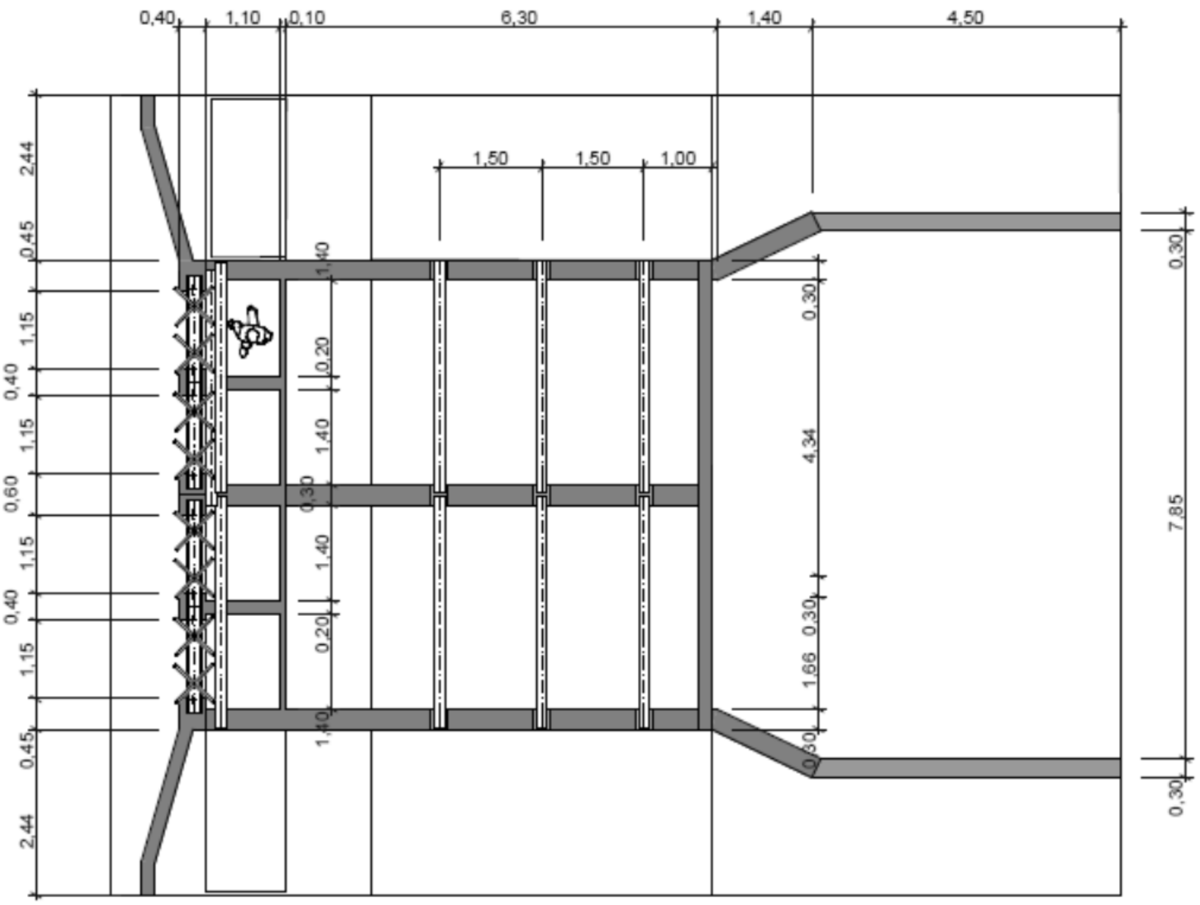
Appendix C - Lake Naivasha Wetland Restoration Project: Phase II Design

Source: Marula Estates (2013).

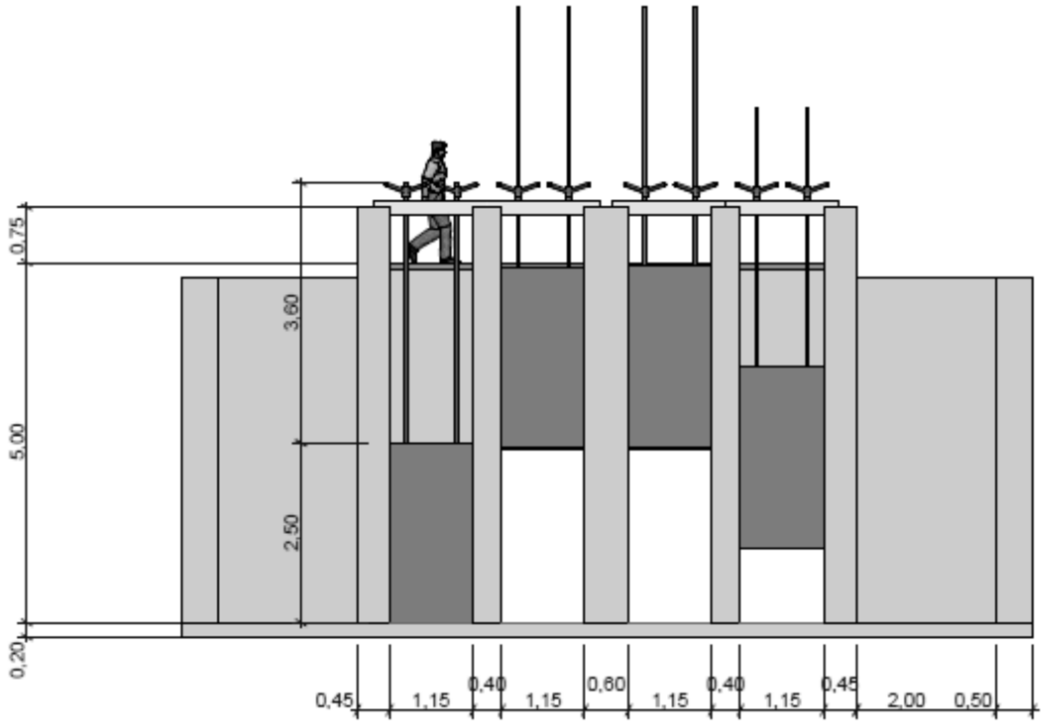
Inlet construction



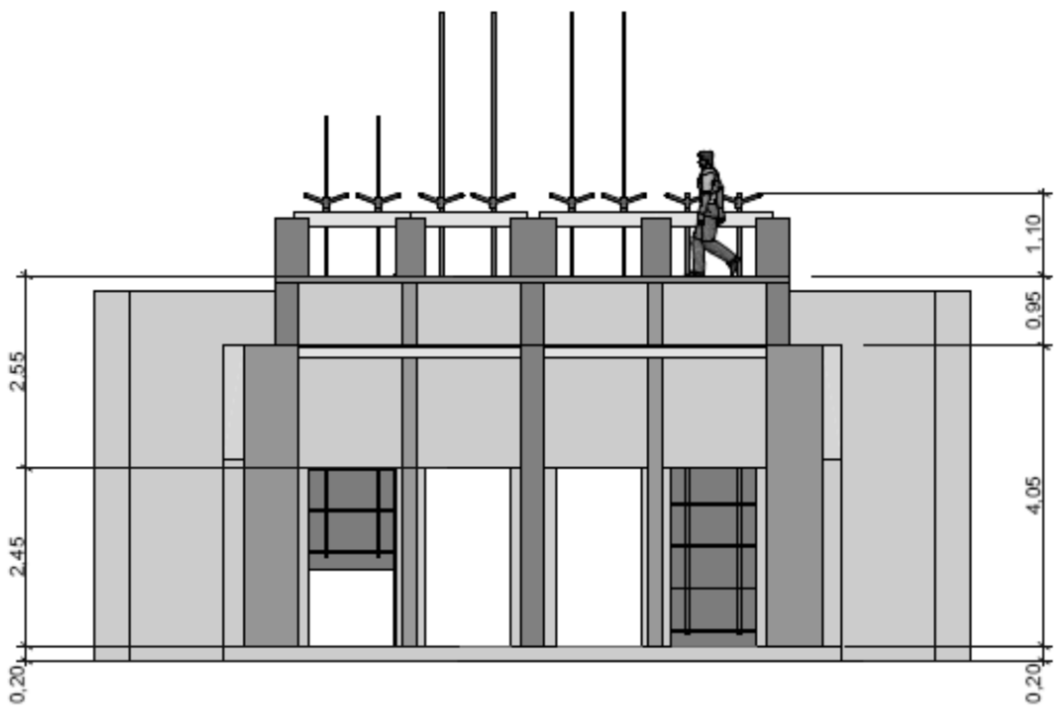
APPENDIX FIGURE 4: INLET CONSTRUCTION - SIDE VIEW



APPENDIX FIGURE 5: INLET CONSTRUCTION - TOP VIEW

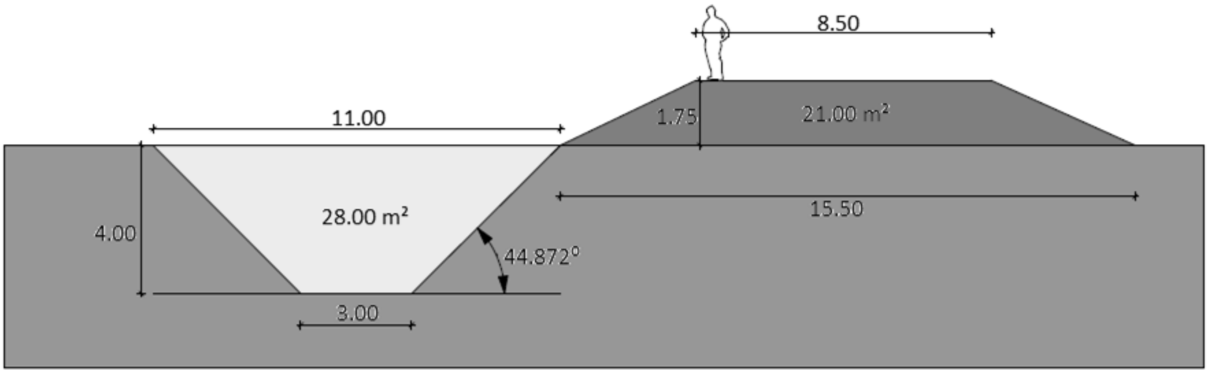


APPENDIX FIGURE 6: INLET CONSTRUCTION - FRONT VIEW



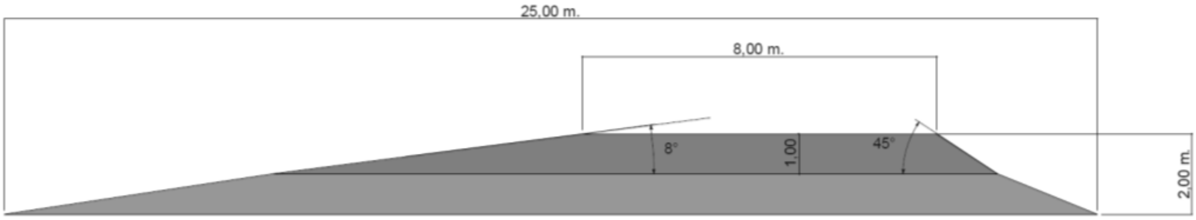
APPENDIX FIGURE 7: INLET CONSTRUCTION - FRONT VIEW

Spillway channel

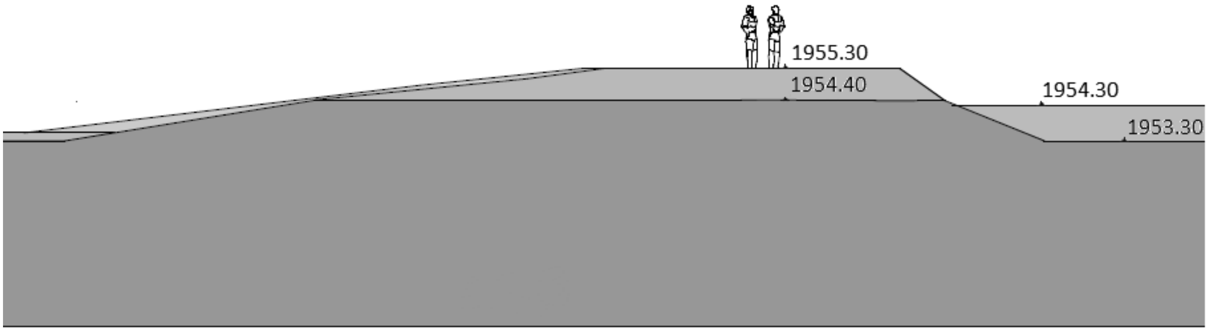


APPENDIX FIGURE 8: SPILLWAY CHANNEL DIMENSIONS

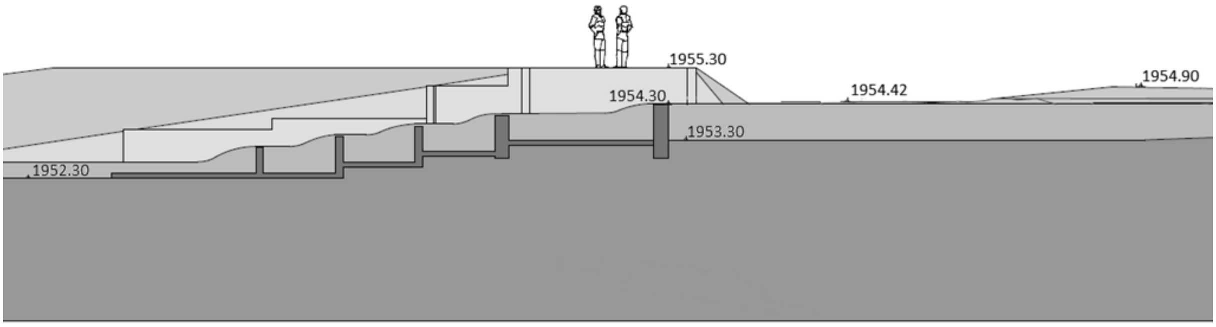
Dike



APPENDIX FIGURE 9: DIKE DIMENSIONS

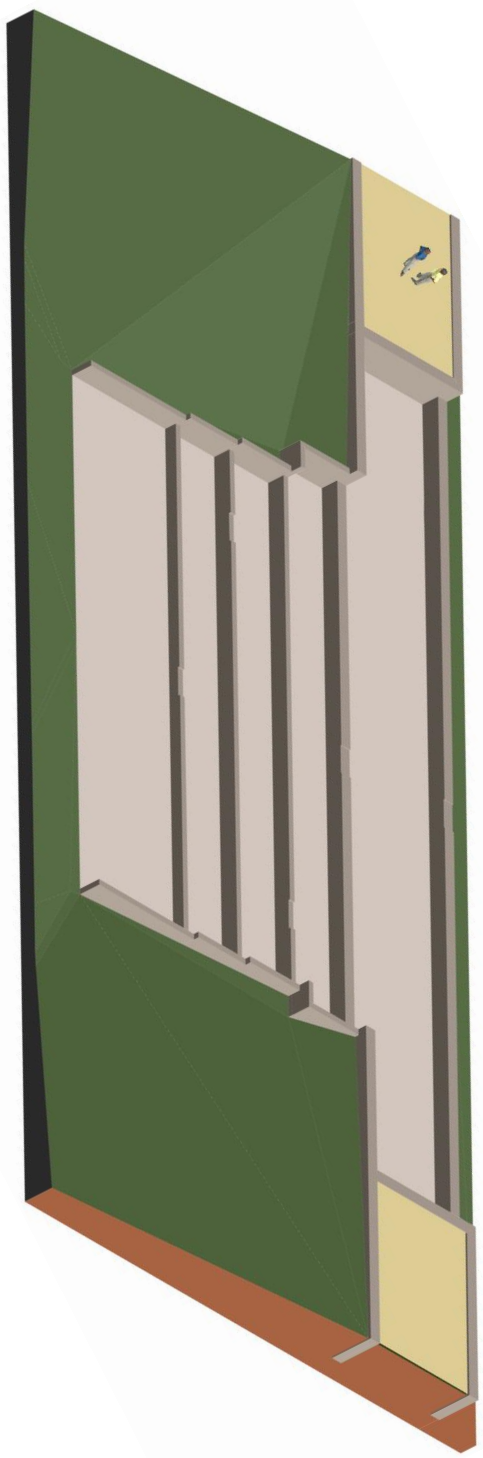


APPENDIX FIGURE 10: DIKE LEVELS



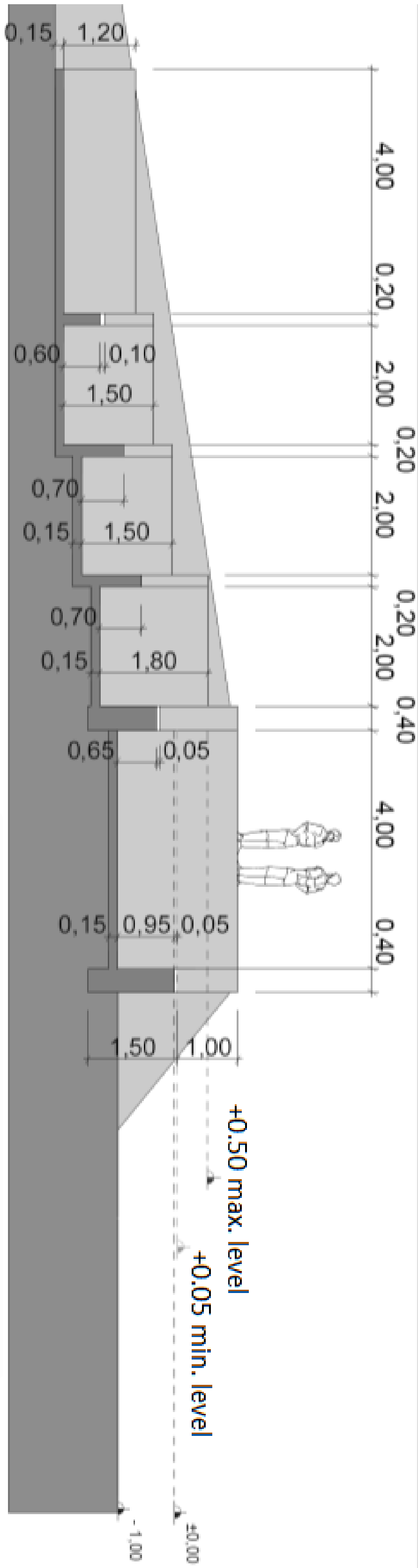
APPENDIX FIGURE 11: OUTLET CONSTRUCTION LEVELS

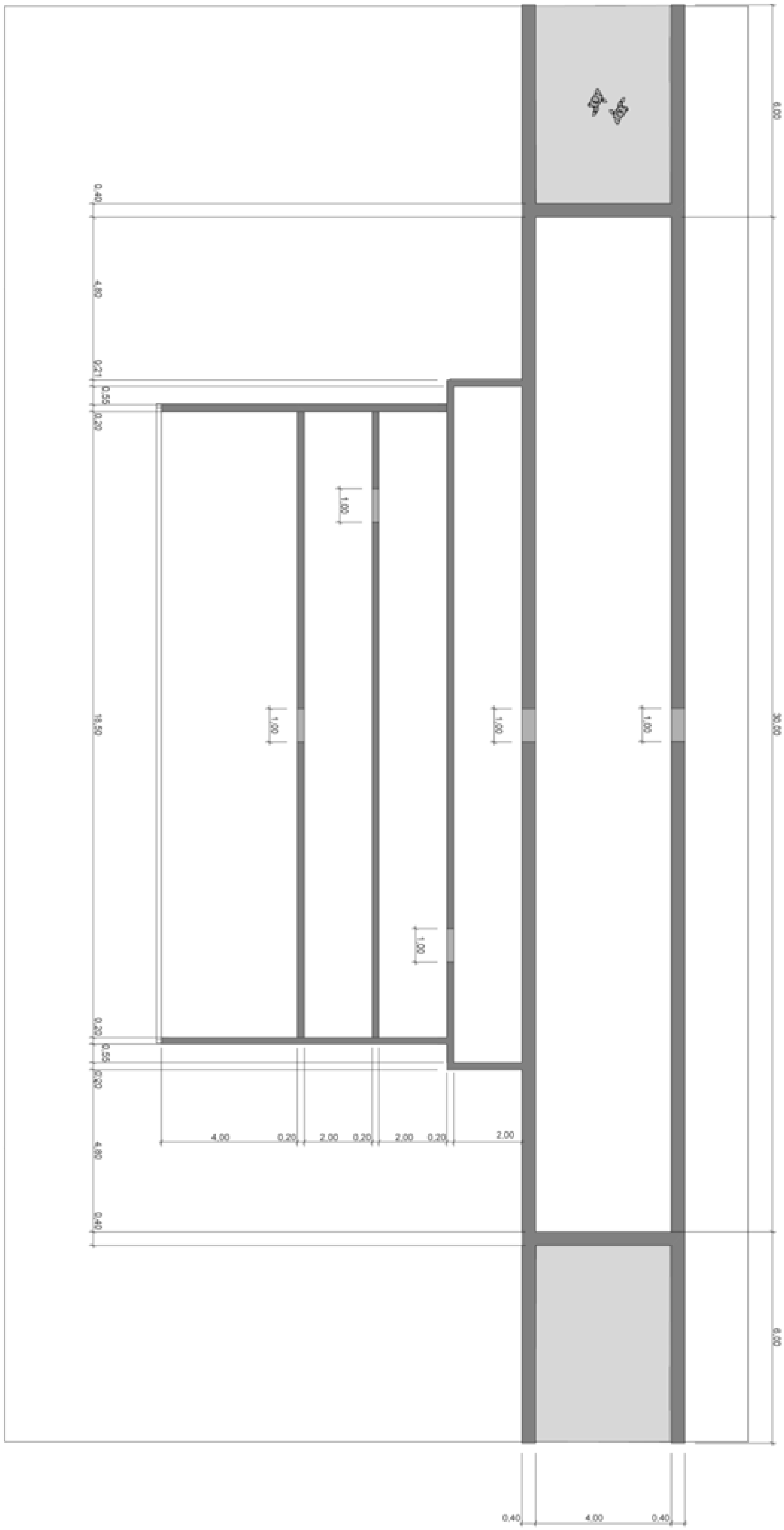
OUTLET CONSTRUCTION



APPENDIX FIGURE 13: OUTLET CONSTRUCTION OVERVIEW

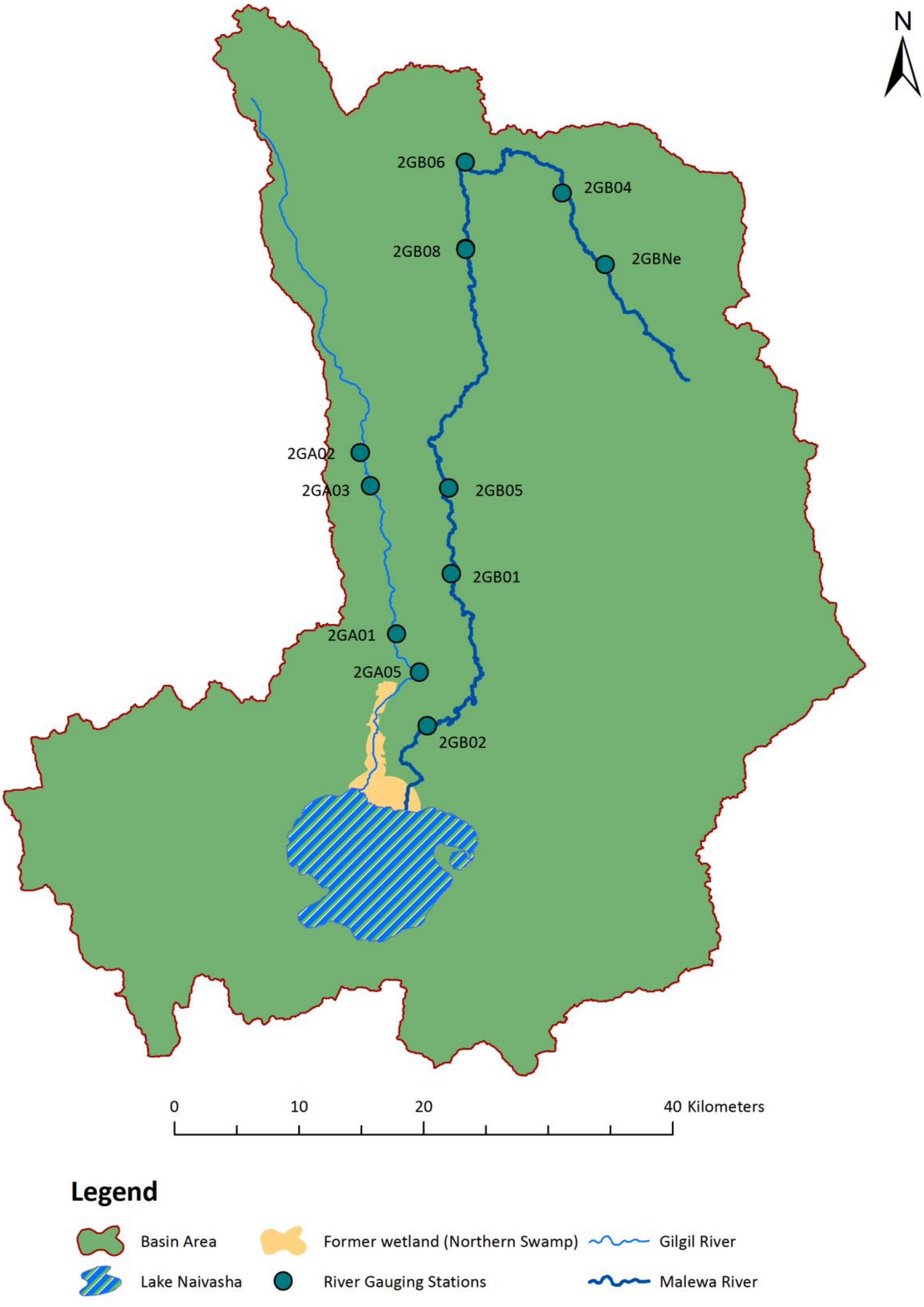
APPENDIX FIGURE 12: OUTLET CONSTRUCTION DIMENSIONS





APPENDIX FIGURE 14: OUTLET CONSTRUCTION - TOP VIEW

APPENDIX D - RIVER GAUGING STATIONS LOCATIONS



APPENDIX FIGURE 15: LOCATIONS RIVER GAUGING STATIONS

APPENDIX E – SOBEK SIMULATION EQUATIONS

The equations used to perform the calculations in the 'simulation' task block are explained for the hydraulic part and the sediment part. To calculate the flow velocity and water depth, the one-dimensional flow is described by two equations, of which the first is the momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + g * A_f * \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 R A_f} - W_f \frac{\tau_{wi}}{\rho_w} = 0$$

with term one describing inertia, term two convection, term three water level gradient, term four bed friction and term five wind friction (which is not taken into account in this research)

and the second is the mass continuity equation:

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

The symbols used and their units are presented in Table 4.

The sediment transport capacity is calculated according to the following equation developed by van Rijn:

$$T_v = 0.053 * \frac{T_{gr}^{2.1}}{D_{gr}^{0.3}} \sqrt{(s-1) * g} * D_{50}^{1.5}$$

$$T_{gr} = \frac{u_*^2 - u_{*c}^2}{u_{*c}^2} \; if \; u_*^2 > u_{*c}^2$$

$$T_{gr} = 0 \; if \; u_*^2 \leq u_{*c}^2$$

$$u_* = \frac{u * \sqrt{g}}{C}$$

$$C = 18 * \log \frac{12 * R}{3 * D_{90}}$$

$$D_{gr} = D_{50} * \left(\frac{(s-1) * g}{v^2}\right)^{1/3}$$

$$s = rs/rw$$

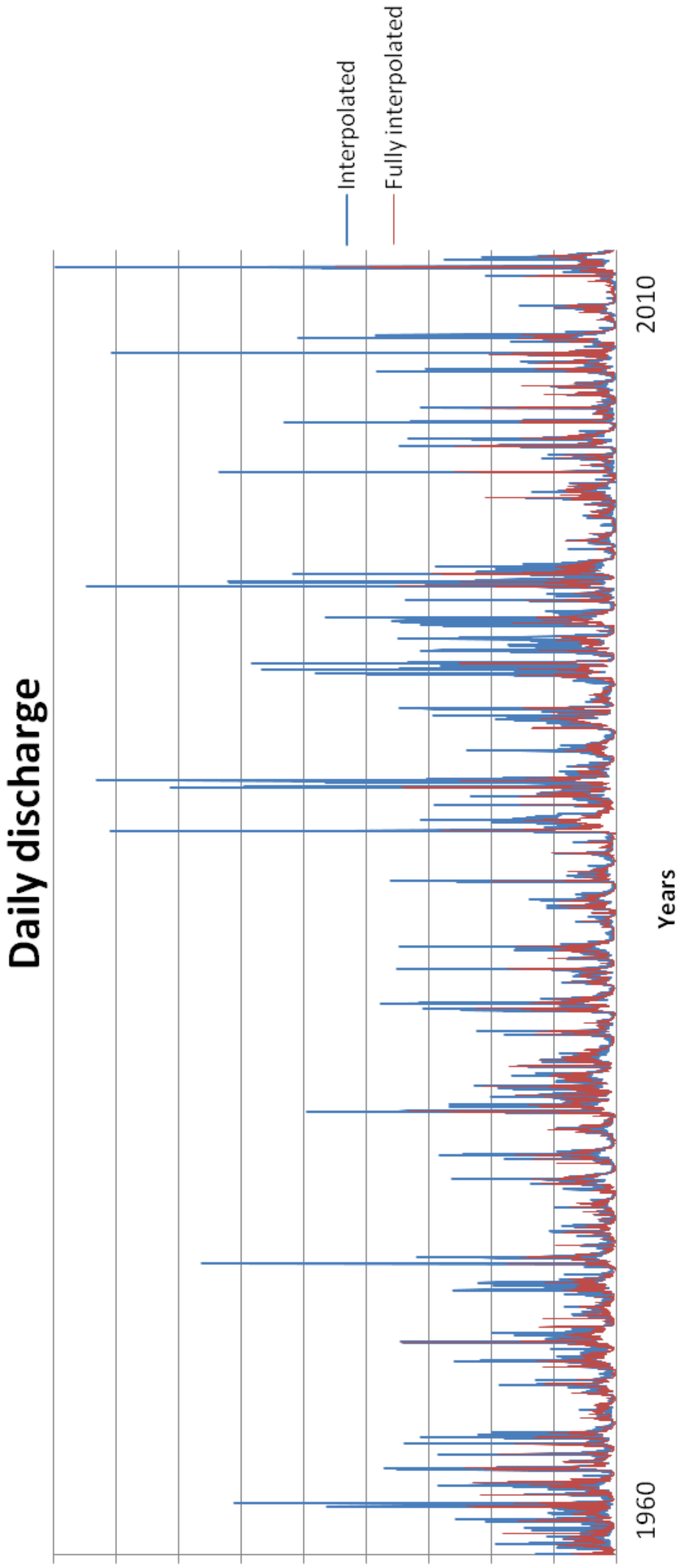
$$u_{*c} = \sqrt{\theta_{cr} * (s-1) * g * D_{50}}$$

$$\begin{array}{ll} \theta_{cr} = 0.24 * D_{gr}^{-1} & if \; D_{gr} \leq 4 \\ \theta_{cr} = 0.14 * D_{gr}^{-0.64} & if \; 4 < D_{gr} \leq 10 \\ \theta_{cr} = 0.04 * D_{gr}^{-0.1} & if \; 10 < D_{gr} \leq 20 \\ \theta_{cr} = 0.14 * D_{gr}^{-0.64} & if \; 4 < D_{gr} \leq 10 \\ \theta_{cr} = 0.013 * D_{gr}^{-0.29} & if \; 20 < D_{gr} \leq 150 \\ \theta_{cr} = 0.055 & if \; D_{gr} > 150 \end{array}$$

APPENDIX TABLE 1: UNITS AND MEANING OF SYMBOLS USED IN EQUATIONS

Symbol	Meaning	Units
t	Time	s
x	Distance	m
Q	Discharge	m^3/s
$\mathbf{A_f}$	Wetted area	m^2
g	Gravitational acceleration	m/s^2
h	Water height	m
C	Chézy coefficient	$m^{1/2}/s$
R	Hydraulic radius	m
$\mathbf{q_{lat}}$	Later discharge per unit length	m^2/s
$\mathbf{T_{vr}}$	Sediment transport capacity per m bed width	m^2/s
$\mathbf{T_{gr}}$	Critical transport velocity	-
$\mathbf{D_{gr}}$	Grain size under water	-
s	Relative density	-
$\mathbf{D_{50}}$	Grain diameter at which 50% of the grains is smaller	m
$\mathbf{D_{90}}$	Grain diameter at which 90% of the grains is smaller	m
u	Average flow velocity	m/s
$\mathbf{u_*}$	Shear stress velocity	m/s
$\mathbf{u_{*c}}$	Critical shear stress velocity	m/s
v	Kinematic viscosity	m^2/s
$\mathbf{r_s}$	Density of sediment	kg/m^3
$\mathbf{r_w}$	Density of water	kg/m^3
$\boldsymbol{\theta}_{cr}$	Critical shear stress	N/m^2

APPENDIX F - (FULLY) INTERPOLATED DISCHARGE SERIES

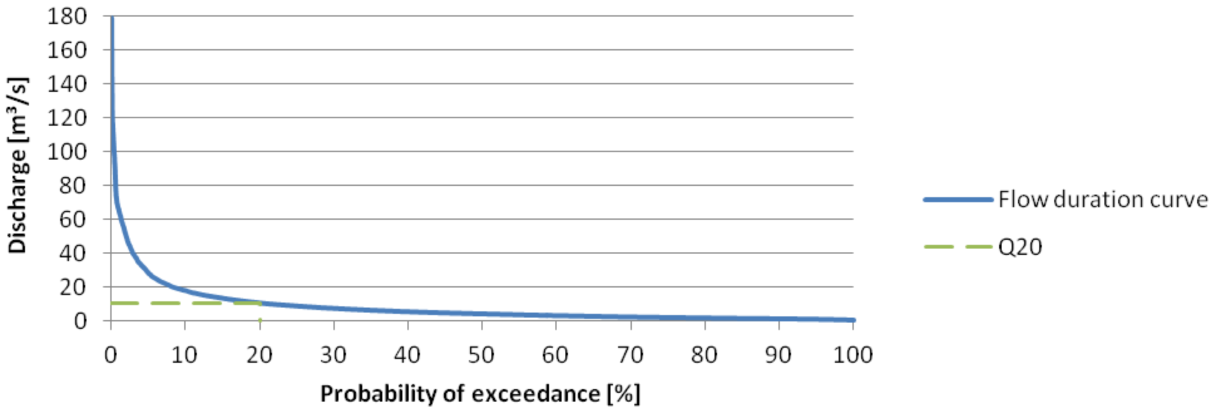


APPENDIX FIGURE 16: MALEWA RIVER DISCHARGE SERIES AT 2GB01

Appendix G - Flow duration curve

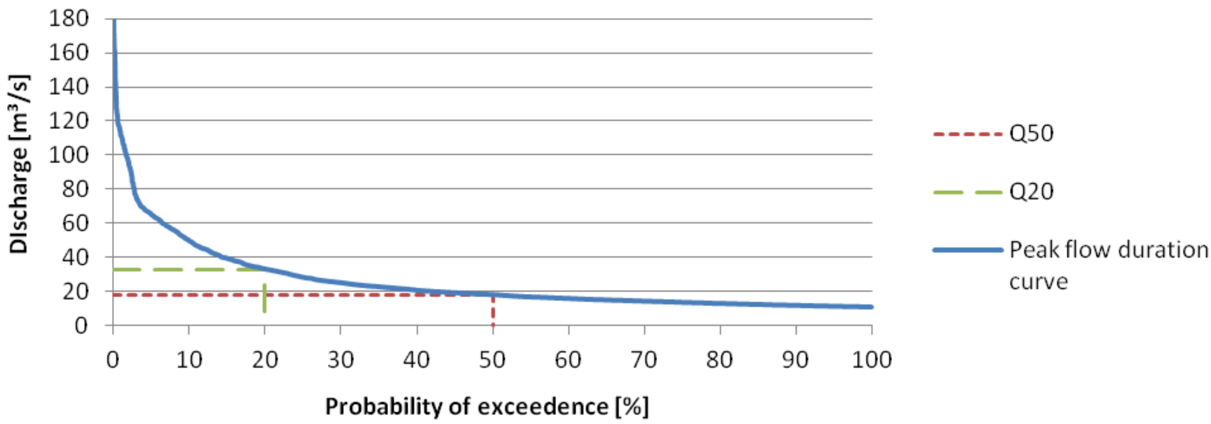
To produce the flow duration curves, the method of Gumbel is used (Gumbel, 1941). In short, the steps in this method are to sort the discharges in descending order and calculate the exceedance probability. This is done by dividing the rank number by the total amount of discharge values +1, and then multiplied by 100%. This gives the probability of exceedance for each discharge, and these results are presented in the figures below.

Based on the water allocation plan presented by the Water Resources Management Authority (Water Resources Management Authority, 2010), in which a flood flow is defined as the flow being exceeded only 20% of the time (Q_{20} flow), the height of the representative discharge peak is determined. Based on a Q_{20} flow and the interpolated discharge series, a peak flow is defined as a discharge exceeding 10.6 m³/s. The flow duration curve including the Q_{20} - flow are presented in this first figure below:



APPENDIX FIGURE 17: FLOW DURATION CURVE AT 2GB01

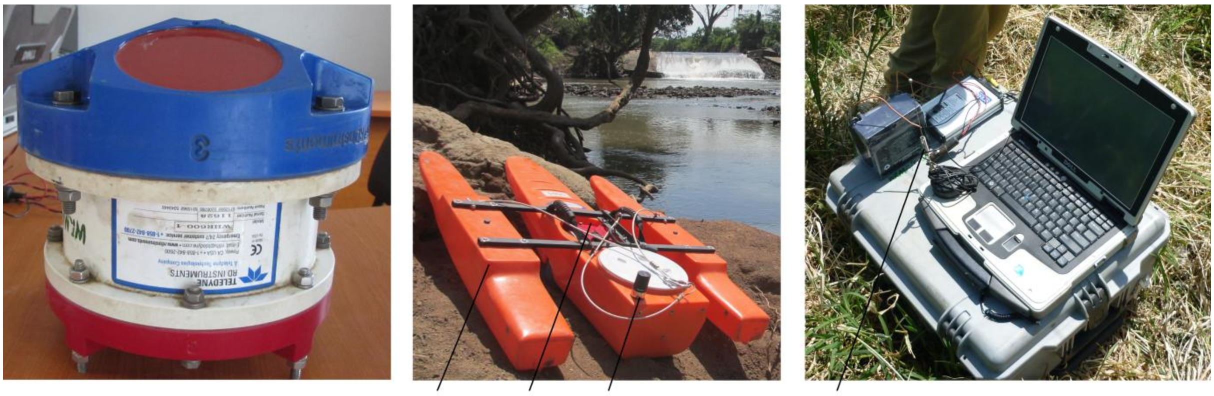
To determine the frequency of occurrence of peak flows, a peak flow duration curve is made. The figure below represents the occurrence of peak flows, e.g. Q50 represents a peak flow that is exceeded 50% of the time, the Q20 represents a peak flow that is exceeded only 20% of the time.



APPENDIX FIGURE 18: PEAK FLOW DURATION CURVE AT 2GB01

Appendix H - ADCP cross-section measurements

The basic theory of the functioning of the ADCP is the transmitting of bursts of sounds, called pings, at fixed intervals and frequency into the water column. Suspended particles in the water column, moving with the water current, reflect these pings back to the ADCP which causes a Doppler shift. Based on this Doppler shift together with the timing of the echoes the ADCP calculates the water velocity for each depth in the water column, the current direction and the water depth (Teledyne RD Instruments, 2011). Via a wireless transmitter in the boat, the gathered data is sent to a receiver connected to a laptop. Software called WinRiver II processes and saves the gathered data, which can be further processed after the field work.



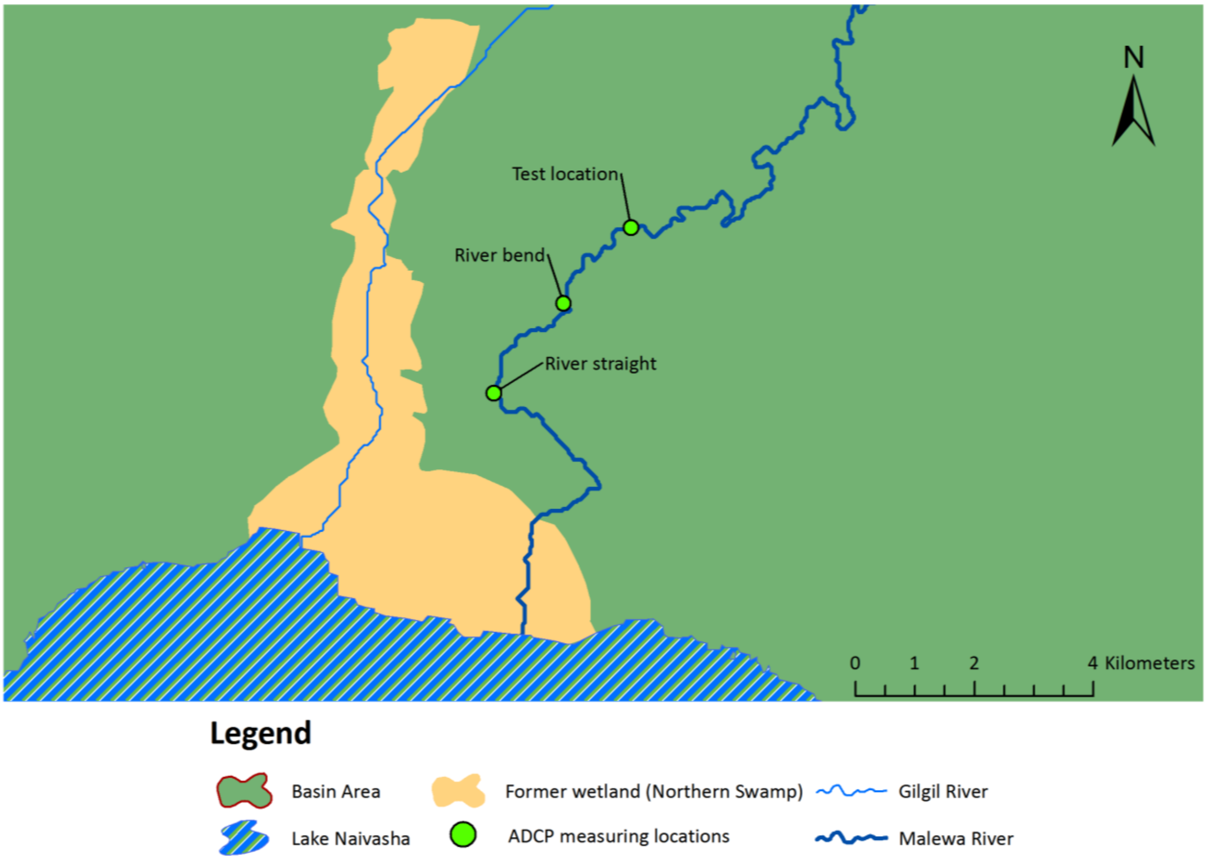
APPENDIX FIGURE 19: CROSS-SECTION MEASUREMENT TOOLS

ADCP's can be operated in several ways, but in this case the ADCP was mounted in a boat which was secured to a rope that was tied across the river. This rope had to keep the boat in a straight line to increase the accuracy of the measurement, but also served as a security to prevent it from being dragged down the river. To the boat, two additional ropes were tied that were operated by two people positioned at both sides of the river to navigate the boat across. The ADCP, boat including ADCP and transmitter, and the receiver connected to the laptop are shown in the figure. For each cross-section, four transects were recorded to gain accurate results which are included in Appendix G.

The above described is a theoretical presentation of how to use the ADCP, in the field however there were some limitations and challenges that affected the measurements. Due to the 1998 El Nino rains which caused high river discharges, the river bed has eroded to depths about eight meter below ground level (Harper et al., 2004), while the maximum water depth during the field work was not even 1.5 meter. Therefore the cross-section dimensions above the water level had to be determined with the use of a measuring tape and based on estimates, which has affected the accuracy. Another challenge was the limited accessibility of the river channel due to the dense vegetation and the steep, almost vertical, river banks. The latter in combination with the presence of wildlife made it impossible to measure the cross-section dimensions downstream of the proposed inlet construction location.

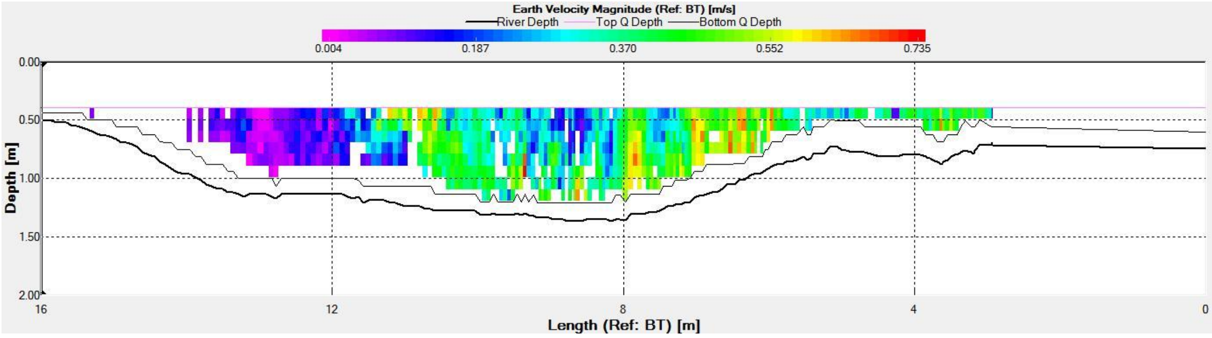
In spite of the challenges, sufficient data was gathered to determine a representative schematization of the cross-section. Although the downcutting of the river bed was an undesirable event, it has led to almost uniform dimension of the channel cross-section upper half, the river banks. The lower half of the channel cross-section, including the river bed, is more variable along the river, but these dimensions were recorded with the use of the ADCP.

Locations ADCP measurements and sediment sample

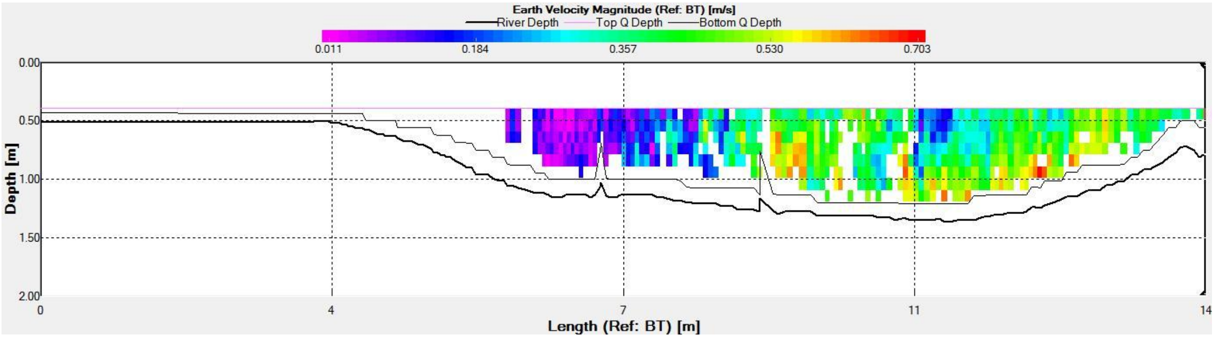


APPENDIX FIGURE 20: LOCATIONS ADCP MEASUREMENTS

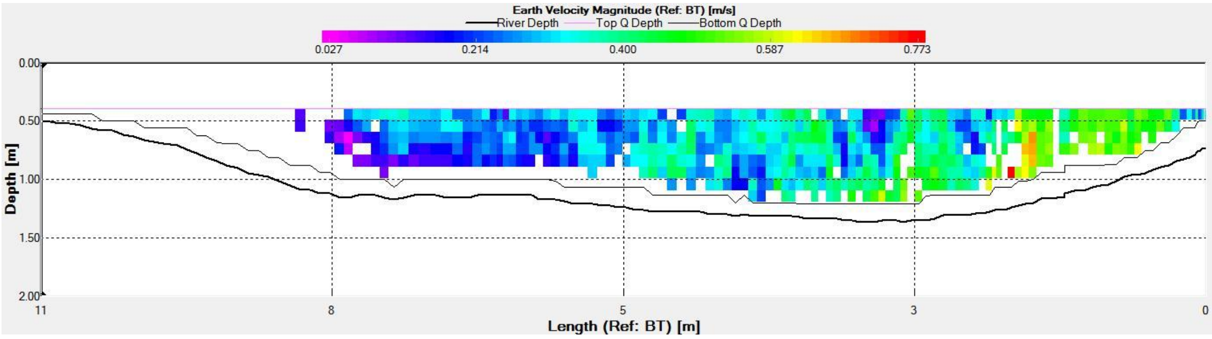
RIVER BEND CROSS-SECTION DIMENSIONS



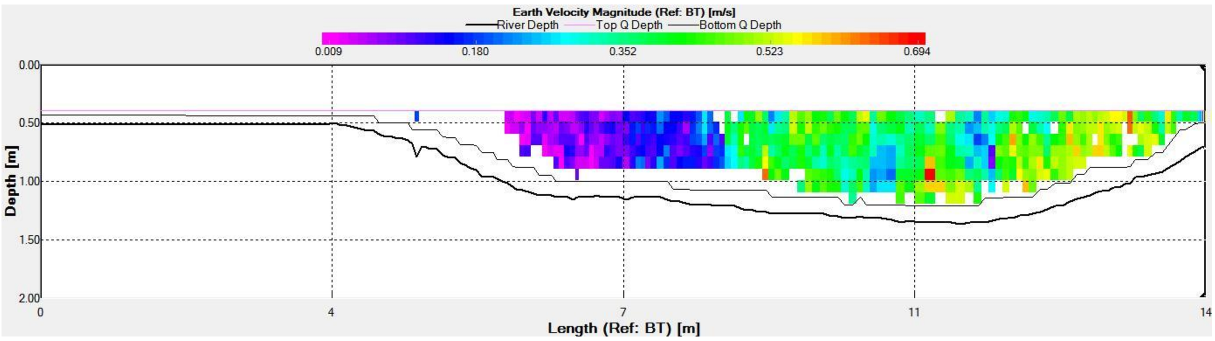
APPENDIX FIGURE 21: RIVER BEND - TRANSECT 1



APPENDIX FIGURE 22: RIVER BEND - TRANSECT 2

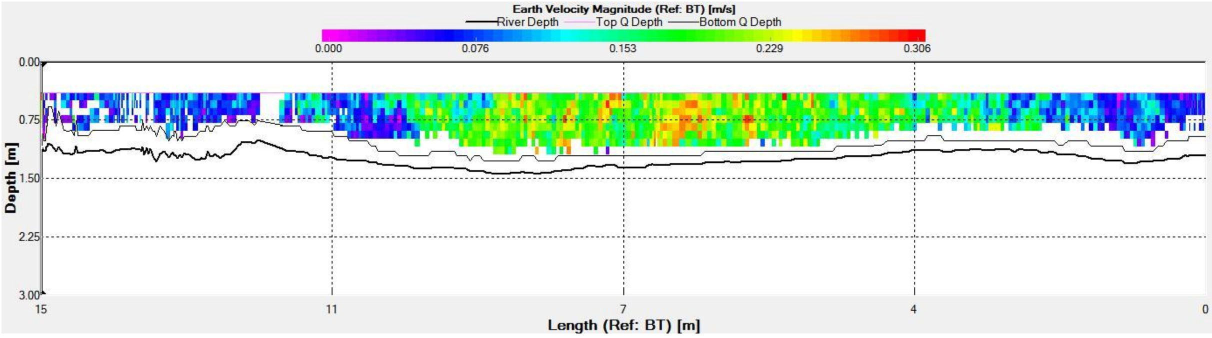


APPENDIX FIGURE 23: RIVER BEND - TRANSECT 3

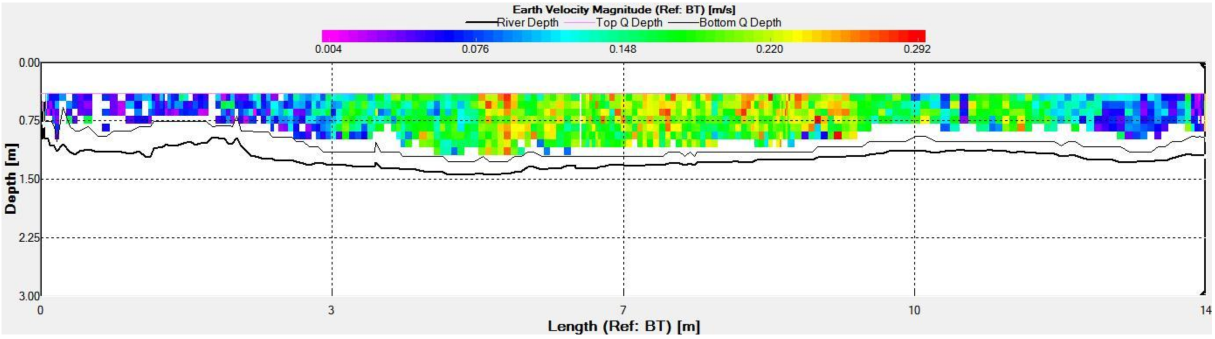


APPENDIX FIGURE 24: RIVER BEND - TRANSECT 4

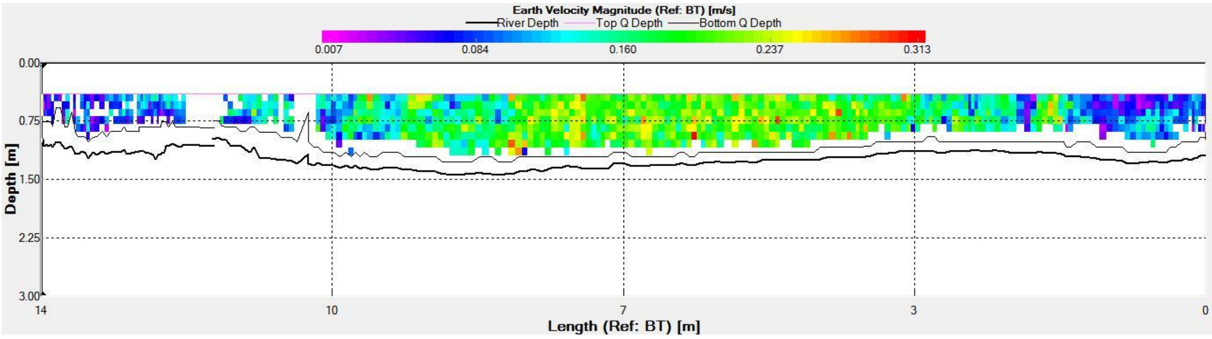
RIVER STRAIGHT CROSS-SECTION DIMENSIONS



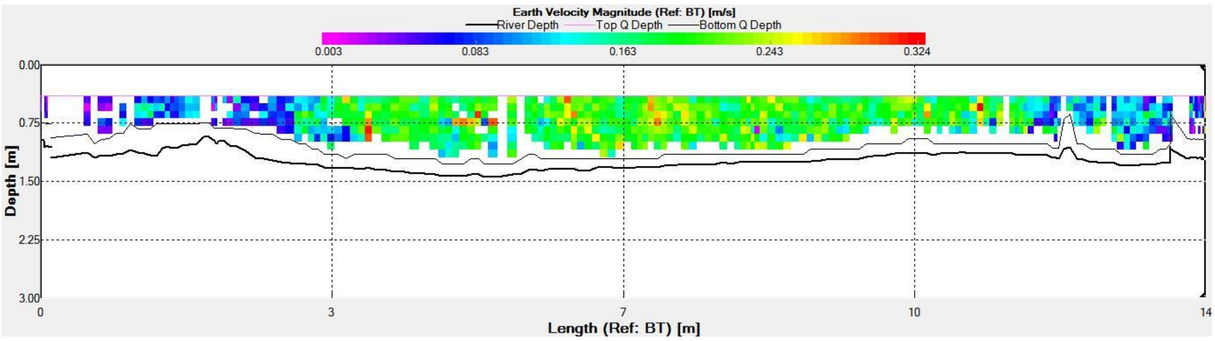
APPENDIX FIGURE 25: RIVER STRAIGHT - TRANSECT 1



APPENDIX FIGURE 26: RIVER STRAIGHT - TRANSECT 2



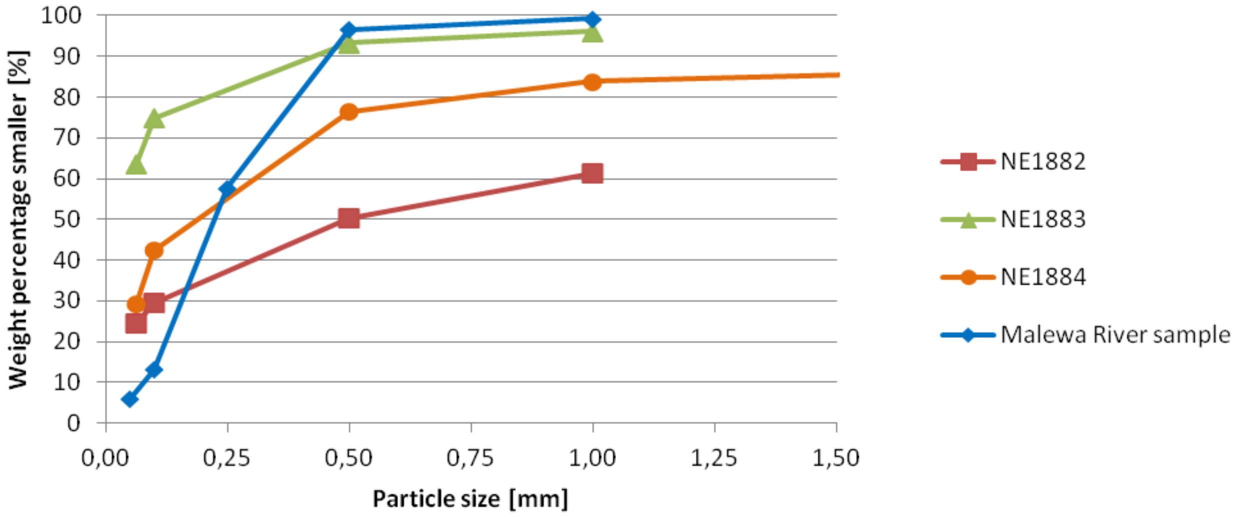
APPENDIX FIGURE 27: RIVER STRAIGHT - TRANSECT 3



APPENDIX FIGURE 28: RIVER STRAIGHT - TRANSECT 4

APPENDIX I – PARTICLES SIZE DISTRIBUTIONS

Based on sediment sample data received from the Fisheries Department (personal communication), the following distributions have been created. From these particle size distributions, the sediment particle size range is determined from which the values for the particle size for scenario's 1a and 1b are extracted.



APPENDIX FIGURE 29: PARTICLE SIZE DISTRIBUTIONS

APPENDIX J – DISCHARGE RATING CURVE LOCATION INLET CONSTRUCTION

To determine from which discharge on it is possible to divert water from the Malewa River through the inlet construction into the spillway channel, a discharge rating curve is made for the location of the inlet construction (indicated as 'River straight' in Appendix H).

This discharge rating curve is made, based on the following equation proposed by Manning, with the parameters and their values in Appendix Table 2

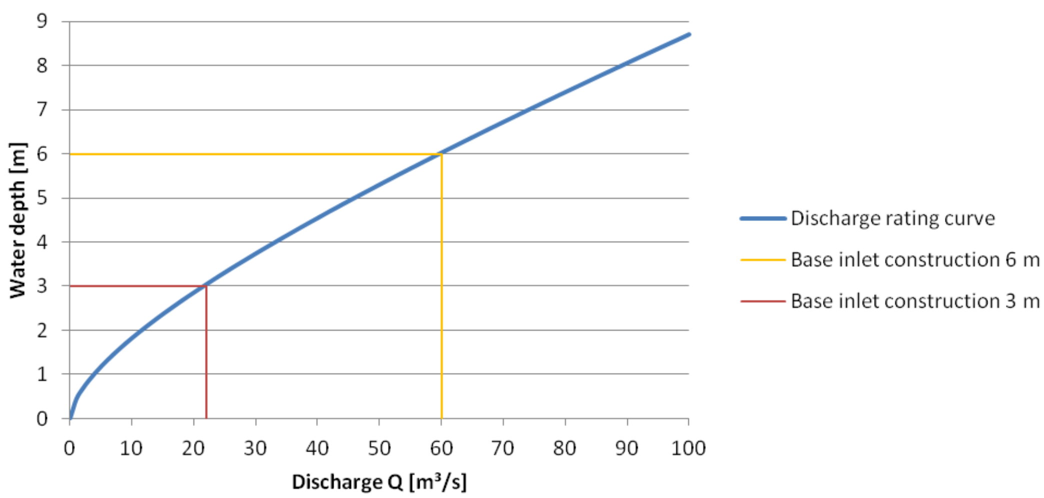
$$Q = \frac{1}{n} * \frac{A^{\frac{5}{3}}}{P^{\frac{2}{3}}} * S_0^{\frac{1}{2}} \quad \text{which can be rewritten as} \quad \frac{(B*h)^{\frac{5}{3}}}{(B+2*h)^{\frac{2}{3}}} = \frac{n*Q}{\sqrt{S_0}}$$

APPENDIX TABLE 2: UNITS AND MEANING OF SYMBOLS USED IN EQUATIONS

Symbol	Meaning	Units	Value
Q	Discharge	m^3/s	Variable
n	Manning coefficient	-	0.2
A	Cross-section surface area	m^2	Variable
P	Wetted perimeter	m	Variable
S0	Bed slope	-	0.0017
B	Channel width	m	20
h	Water depth	m	Variable

To establish the relation between the discharge and the water depth, the interpolated Malewa River discharge series (Meins, 2013) are used. The river bed slope is estimated at 0.0017, which is explained in Appendix N. The channel width is estimated at 20 meters, based on the ADCP measurements and the observations during the field work. The Manning coefficient value is estimated based on the extreme high discharge in April 2013, during which the discharge was estimated at approximately 100 m^3/s and the channel, with an approximate depth of 9-10 meters, was completely filled with water a few kilometers upstream of where the inlet construction is going to be constructed. To establish a water depth of 9 meters with a discharge of 100 m^3/s, the estimate for the Manning coefficient is 0.2.

With the values of the parameters known except the water depth, the equation can be solved for a discharge increasing from 0 till 100 m^3/s. This results in the discharge rating curve as presented in Appendix Figure 30.

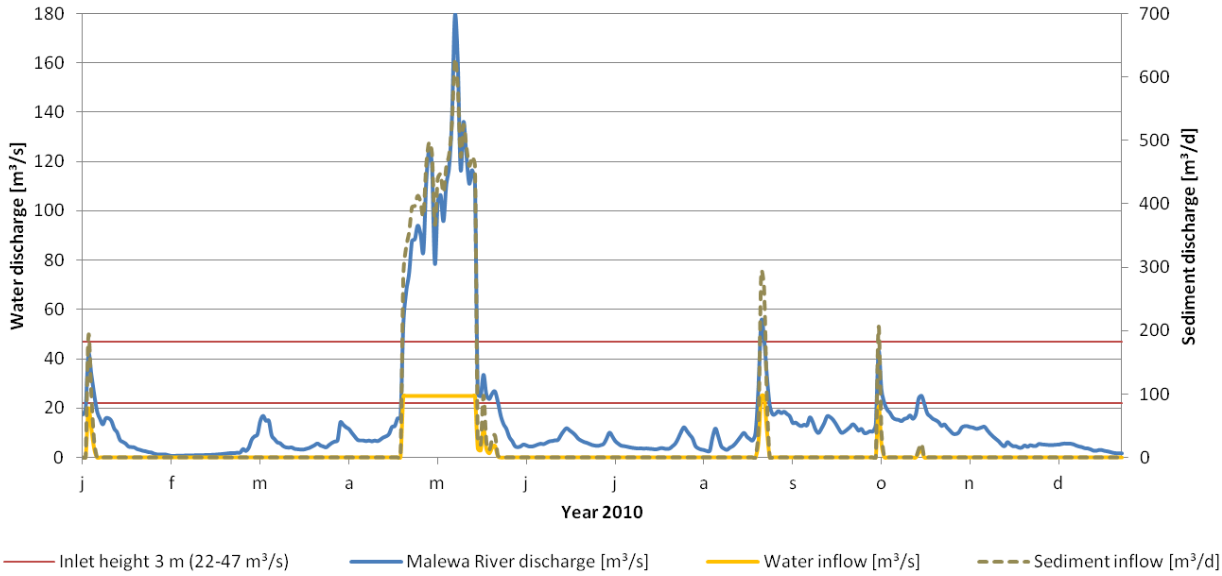


APPENDIX FIGURE 30: DISCHARGE RATING CURVE MALEWA RIVER INLET CONSTRUCTION

APPENDIX K – SHIFT BASE INLET CONSTRUCTION

Constructing the base of the inlet construction at 6 meters height from the Malewa River bed seems to be most feasible and sensible. However, when, due to whatever reason is decided to construct the inlet construction at a lower level in the Malewa River bank, e.g. to increase the amount of water that can be diverted, the inlet construction is constructed at 3 meters height from the Malewa River bed the inflow of water and sediments will increase.

In Appendix Figure 31, just like in Figure 20, the Malewa River discharge is indicated with the blue line. Due to the lowering of the base of the inlet construction, the 'window of discharge' indicated with the red lines, is between 22 and 47 m^3/s based on the discharge rating curve presented in Appendix Figure 30 and with the assumption that the maximum spillway channel discharge remains 25 m^3/s. The water inflow, indicated with the yellow line, now does not only take place in the period from the end of April till halfway May but also in January, August and October. During these periods of water inflow, also sediment inflow takes place which is indicated with the grey dotted line.



APPENDIX FIGURE 31: 2010 SEDIMENT INFLOW INTO LAKE NAIVASHA WITH AND WITHOUT DIVERSION INTO WETLAND

The total amount of sediment diverted to the wetland over 2010 increases to 13188 m^3. The sediment inflow into Lake Naivasha gets reduced with 18%. This is only slightly higher compared to 15% reduction in sediment inflow into Lake Naivasha with the base of the inlet construction at +6 meters.

APPENDIX TABLE 3: 2010 SEDIMENT INFLOW INTO LAKE NAIVASHA WITH AND WITHOUT DIVERSION INTO WETLAND

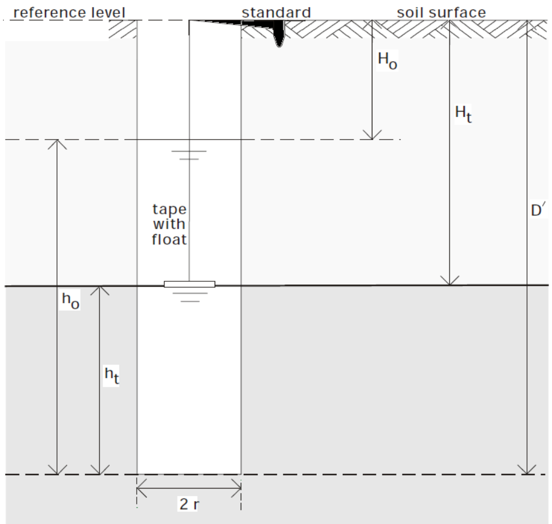
Sediment inflow Lake Naivasha without wetland (suspended + 10% bed load) [m³]	Sediment inflow into wetland, inlet at +3m [m³]	Remaining sediment inflow Lake Naivasha [m³]	Sediment inflow reduction into Lake Naivasha [%]
73930	13188	60742	18

APPENDIX L – INFILTRATION TEST

To determine the infiltration of water into the ground in the former Northern Swamp, an inversed auger-hole infiltration test is done.

The test is done according to the method described in Oosterbaan (1994). With the use of an auger, a hole is made in the soil which is then filled with water several times until the soil around the hole is saturated. After the last refilling, the rate of the drop of the water level in the hole is measured with the use of a dipper.

In the table the results of the field work are summarized, with in the figure on the right an overview of the used symbols.

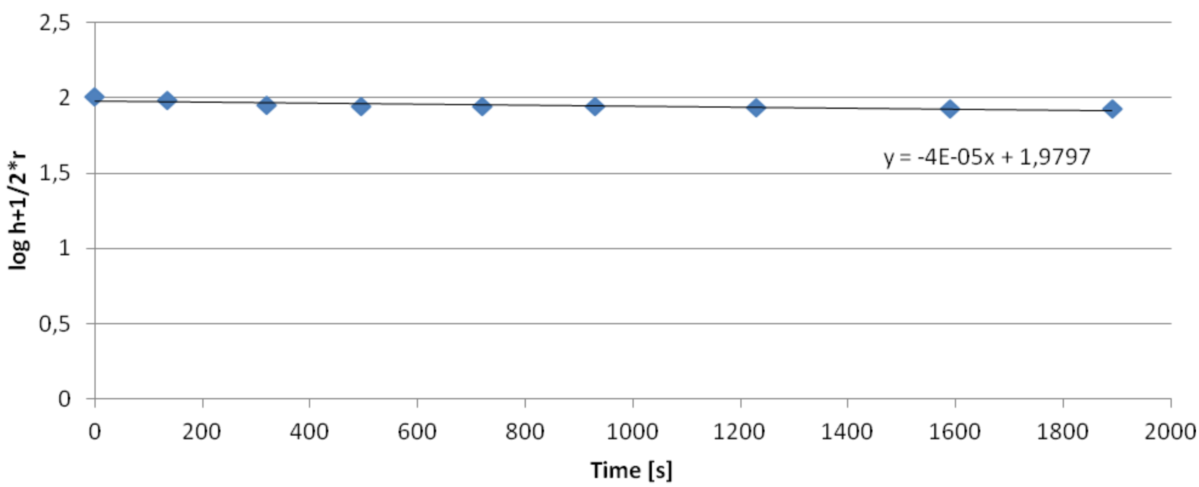


APPENDIX FIGURE 32: METHOD INFILTRATION TEST

APPENDIX TABLE 4: RESULTS INFILTRATION TEST

Ht [cm]	Time [s]	ht [cm]	h+1/2*r (r=3cm)	log (h+1/2*r)
0 (H0)	0	100 (D' & h0)	101,5	2,006466042
5	135	95	96,5	1,984527313
12	320	88	89,5	1,951823035
13	495	87	88,5	1,946943271
14	720	86	87,5	1,942008053
14,5	930	85,5	87	1,939519253
15,5	1230	84,5	86	1,934498451
17	1590	83	84,5	1,926856709
17,5	1890	82,5	84	1,924279286

The data are plotted with h+ ½ r on the log y-axis and time on the x-axis. The graph yields a straight line which means that the infiltration rate is more or less constrant because the soil below and around the hole is practically saturated. The infiltration rate (K) can now be calculated with: $K = 1.15 * r * \tan\alpha$, with α the slope of the tangent line connection the data points -> $K = 1.15 * 3 * -\tan -4E - 05 \approx 0.000138\ cm/s$.

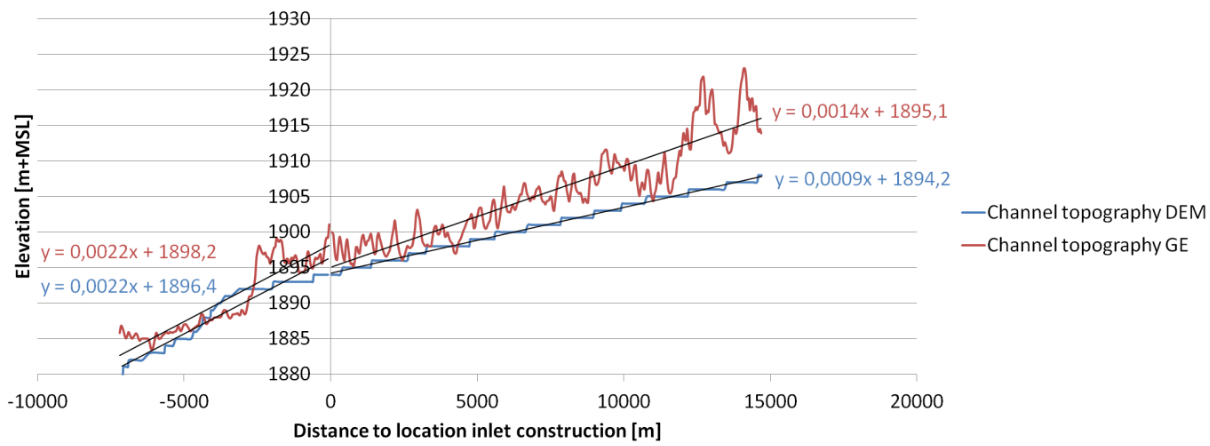


APPENDIX FIGURE 33: DATA POINTS INFILTRATION TEST

APPENDIX M - MALEWA RIVER BED SLOPE

With the use of ArcMap, the DEM and the Malewa River course the channel topography is determined in the following way. In ArcMap the Malewa River is divided into sections, with each section starting in a bend and ending in the subsequent bend. The location of the midpoint of each section is then connected to the DEM, and from the DEM the elevation of each location is extracted. These elevations are plotted against the river course, with the inlet construction location as zero, the upstream stretch as positive and the downstream stretch as negative. Google Earth offers a feature with which the elevation profile of a user-defined path can be determined. This data is exported to e.g. Excel with the use of the tool Geocontext-Profiler[1]. Again the elevations are plotted against the river course, with the inlet construction location as zero, the upstream stretch as positive and the downstream stretch as negative.

The results of the elevation extracted from the DEM and Google Earth are presented in Appendix G. From this graph it can be observed that the river bed slope upstream of the inlet construction location is slightly less steep compared to the river bed slope downstream of the inlet construction location. Therefore, to identify a representative slope a distinction is made between upstream and downstream of the inlet construction location. For the downstream section, with the use of the DEM as well as with the use of Google Earth the slope is approximately 0.0022. For the upstream section, with the use of the DEM the slope is calculated at 0.0009, while this is 0.0014 with the use of Google Earth. Combining these two methods gives an approximate slope of 0.0012 for the upstream section. An overview of the river bed slopes based on the two methods is presented in the figure below:



APPENDIX FIGURE 34: MALEWA RIVER BED SLOPE BASED ON DEM AND GOOGLE EARTH

APPENDIX TABLE 5: MALEWA RIVER BED SLOPE BASED ON DEM AND GOOGLE EARTH RESULTS

Slope [-]		Method			Methods & sections combined
		DEM	Google Earth	Combined	
Section	Downstream	0.0022	0.0022	0.0022	
	Upstream	0.0009	0.0014	0.0012	0.0017

1 http://www.geocontext.org/publ/2010/04/profiler/en/