

Morphology of the Mara River

Assessment of long term
morphology and the
consequences for
Environmental Flow
studies

Msc Thesis - B.M. Stoop

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Morphology of the Mara River

Assessment of the long term morphology and
the effect on the riverine physical habitat

by

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Picture cover page: Taken by Ryan Harvey, taken on the 22th of April 2007, during a flight from Masai Mara to Rusinga Island.

Preface

Before you lies the report 'Morphology of the Mara River', which is the result of a challenging but rewarding research journey through the fascinating Mara River – sometimes literally. This research journey started in November 2015, when I was introduced to the team managing the MaMaSe project. The enthusiasm and dedication of this team, along with the project's potential impact on the ecology of the Masai-Serengeti ecosystem has been a great motivator for me up and until this very moment. I am especially grateful for Kelly, John, Michael from IHE Delft. And especially for participating in the EFA field surveys, where I got to meet great people and learnt so much from all their different fields of expertise. So Barabas, Patrick, James, Gordon, Bennie, Frank, Kate, Lauren, thank you a lot for not only improving my understanding of the river, but also for making the field visits pleasant and enjoyable. Of course I am also very grateful for all the people I got to know after the EFA field visits, when at first my life was very uncertain. Sanne, Ingrid, Patrick, Tomkin, Anne, Augustine, Lameck, mr. Lubanga, Jacob thanks for showing me around in Kericho and Eldoret and welcoming me with open arms in your culture.

Although the full details of a river's morphology are not easily captured in words, it is no exaggeration to state that my personal understanding of the Mara River has greatly improved. It goes without saying that I have encountered some hurdles during the process. However, I have also come across breathtaking landscapes, impressive wildlife and amazing people during this project, making me realize what is important in life, and which I will keep as a precious memory to supplement this report for years to come. Despite this research being only a small aspect in the context of water allocation planning, I find myself lucky to be able to contribute to current and future efforts of keeping water resources safe and secure, especially in ecologically sensitive areas.

I would like to thank my supervisors (who may have perceived this process as a journey on its own) for supporting me during this project. Michael and John, first of all thank you for giving me the opportunity to take part in the MaMaSe project. I am very grateful for your help on the ecological side of this research, an area to which I have had little exposure before I started this project. Erik, your ideas and expertise on the morphology have been of great support for me, pointing out the roads that could be taken. I have very much valued your help on keeping an eye on the wider picture of this study, as well as your help in detailed modelling the river's branches. Thom, thank you for letting me free to choose my own ways, even though I found that hard at moments. It has been reassuring to realize that your door was always open, especially late in the afternoon. Thanks for giving me the confidence in taking my own path, and being proud of the results.

A big thanks should go out to the people from Unesco, and a lot of various people in the Civil Engineering faculty, old friends and new people who have supported me in various ways throughout the project. These people include my fellow water management students, the hydraulic master students from the third floor, as well as various subject matter experts. Hans van Marel from the remote sensing department, thank you for supporting me in the DGPS survey, and responding on my emails of despair when handling the datalogger. A big thanks to all the people who gave me advice in the last part of the writing, Lauren, Petra and Sandra. Also a big thanks to Floris for this and for his effort to pull me through the and look beyond my perfectionism in the last week, that was awesome. Last but not least, I would like to thank all my friends, fellow students and family for their moral support, I could not have done this without it.

*Bianca,
May 17, 2017*

Abstract

In the Mara River Basin, increasing water abstractions put pressure on the water resources in the Mara River Basin, endangering biodiversity and the Masai-Serengeti ecosystem. Therefore, a Water Allocation Plan (WAP) has to be set up, where the water resources are divided among all stakeholders, one of which being the ecosystem itself. Part of the WAP is the Environmental Flow Recommendation (EFR), which describes the minimum flows to sustain the ecological health of the ecosystem. The interactions between hydrology, morphology and ecology are important for establishing an EFR. To arrive at the EFR for the Mara River, a holistic approach, recognising these interactions should be applied. The aim of the Environmental Flow Assessment (EFA) is to set thresholds for a certain percentage of habitat coverage to sustain important ecological processes. The shape of the river, and thereby the morphology is, (together with the hydrology), the main driver in determining these thresholds. In the current assessment of the morphological aspect of the EFA, the minimum flows are described to sustain the morphological features of the habitat. During the hydraulic modelling, changes of habitat over long-term are not included. However, for the Mara River, it is evident from satellite imagery that the river has been changing in the past, suggesting that long-term processes should be incorporated in the EFA.

It is the aim of this research to assess the influence of changes in flow regime on the long-term morphology for the Mara river basin, thereby concluding on the significance of these effects for the establishment of the EFAs. Both a long-term assessment and local EFA assessments are undertaken and the results are linked to each other. Analytical and numerical calculations for the long-term 1-dimensional sediment transport analysis were conducted. Four reaches along a portion of the main stream of the Mara River are distinguished in the analysis. First, a reference scenario was established based on current discharges and parameters measured during site visits. Scenarios for future discharge regimes, were derived from the EFR. Three discharge scenarios are considered; $Q_{EFA,floods}$ build up by the full EFRs, $Q_{EFA,maintenance}$, build up by only taking into account the maintenance flows, and the 95 percentile of flow (Q_{95}), which is the legislative discharge set by the Kenyan government. The results of the analysis include changes in cross sectional averaged bed levels, velocity, and depth over the length of the river.

Although the river shows signs of historical erosion, also seen from field observations, the current state of the river is expected to be stable, since the riverbed is controlled by bedrock. The result for the equilibrium sediment transport flux for the alluvial reach of the river was comparable to fluxes in other rivers in Kenya. A first indication for the corresponding characteristic time scale for adaptation of the bed level is 1000 years, which indicates the time it takes for half of the total perturbation of the riverbed to respond. These results support the assumption that the river is stable for the current situation. Comparing the calculated discharge scenarios, the Q_{95} and $Q_{EFA,maintenance}$ scenario show high response of the bed level. The $Q_{EFA,floods}$ shows the same pattern of steepening, but the bed level changes are much less. From this result it can be concluded that it is important to establish an EFR, that also considers the floods, recognising the importance of the morphological assessment of the EFA.

This research has taken the first steps in the direction of assessment of river stability in perspective of EFA assessments under data limited circumstances. Unfortunately no further conclusions can be made upon the long-term assessment of the bed level response on a small time scale, therefore improvements of the numerical model are recommended to be made. It is recognised that 2-dimensional processes such as meandering and river widening are important to take into account as well. Moreover, for better understanding and possibly in the future quantification of the morphological processes, it is recommended to build up a data bases including standardized data collected from field surveys of the EFA or monitoring moments after flood events. This can greatly contribute to the understanding and verification of expected morphological processes in the river.

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Introduction

The Mara river is a transboundary river, flowing from the Mau escarpment in Kenya to Lake Victoria in Tanzania. In this transboundary river basin, many stakeholders are dependent on the water resources. The Mara river not only sustains the Masai Mara National Reserve and Serengeti National Park in the middle of the basin, (illustrated in Figure 1.1), but it also provides water to nearly one million people in Kenya and Tanzania (Dutton et al., 2013).

The wildlife and ecology of the national parks are heavily dependent on the water resources of the river basin. Wildebeest and zebras migrate yearly, following the water and fresh grasses. Other demands for the water resources are agriculture up and downstream of the Serengeti National Park, and wetlands with fisheries near Lake Victoria, the downstream border of the river basin. Population growth and increasing agricultural activities are putting pressure on the water resources of the river, and are expected to change the hydrological system (WREM International Inc., 2008). Much research has already been done on the effects of the increasing urban and agricultural land use areas (Mati et al., 2008; Mango et al., 2011; Defersha et al., 2012). The main concerns in the basin are focused on the influence of the land use change on degradation of the wetlands and water quality.

In the perspective of climate adaptation, the Nile Basin Initiative (NBI) has done feasibility studies on the construction of dams in the Mara River and its upstream tributaries to provide water for rural uses and livestock during the dry season (Nile Basin Initiative (NBI), 2014). To date, the plans have not been further investigated after publishing the feasibility reports. These reports recognise that deterioration can be experienced in the areas downstream the of dam.

Under these prospects, the management of the water resources is highly important. In order to better manage the water resources the Water Resources Management Authority (WRMA) which manages the water resources in the Mara River, has partnered up with the Mau Mara Serengeti (MaMaSe) project, led by Unesco-IHE. Amongst other goals they are setting up a well justified WAP, where water abstractions are divided between all stakeholders in the basin, including ecological requirements. In the Mara River, the WAP is especially important because increasing water abstractions are putting pressure on the water resources, and endangering biodiversity and the Masai-Serengeti ecosystem. The goal of the WAP is to protect the basin from the consequences of excessive extractive water uses, which is often at the expense of the local environment. The water resources allocated within the WAP need to be well justified since many of the involved parties are dependent on the water supplied from the river.

1.1. Problem definition

Although the demands for irrigation, industries and other water users can often be assessed in a straightforward manner, there is still much uncertainty about the required amount of water to maintain the river's ecosystem (Wahono et al., 2014). Existing frameworks for the justification of the water requirements for ecology are set up to determine the minimum flow needed for the riverine ecosystem, which are called Environmental Flow Recommendations (EFRs). The minimum magnitude, timing and frequency of the discharge

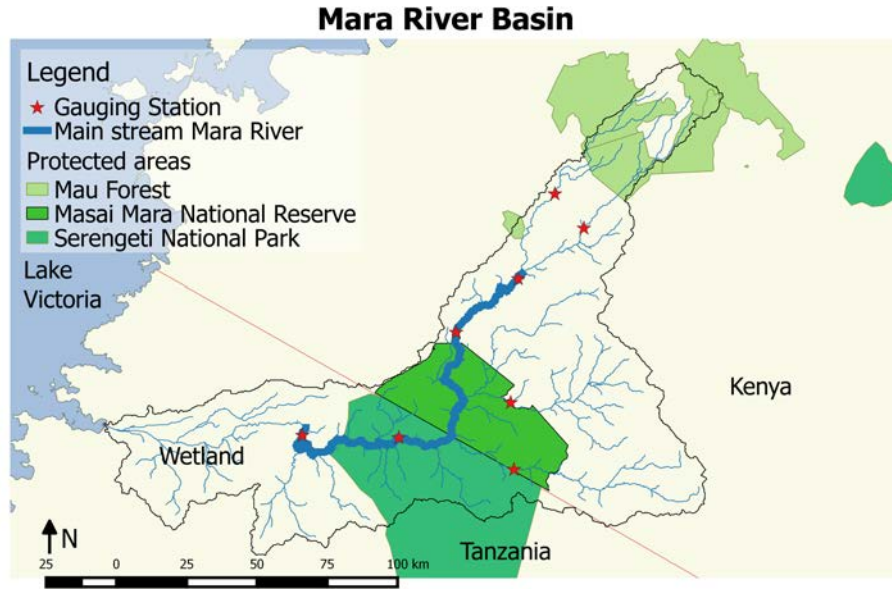


Figure 1.1: Map of the Mara River Basin

needed to keep a healthy riverine ecosystem is described in the EFRs, and the methods to determine these flows are called the Environmental Flow Assessment (EFA). The assessment methods recognise the interactions between hydrology, morphology and ecology, and aim to relate and integrate all these components. The hydrological component is divided into water resources, water quality and hydraulics of the river, where the water resources and quality can be managed by water authorities. The morphology in this relationship represents the state, shape and dimensions of the river bed, influenced by sediment transport processes. The ecology involves responses of fish, macro-invertebrate and vegetation communities. The latter one also interacts with the morphology. An overview of these relationships is given in Figure 1.2. Although quantification of a generalised relationship between all factors remains a challenge (Poff and Zimmerman, 2010; Bunn and Arthington, 2002; Lloyd et al., 2004), it is important for restoration and management of riverine ecosystems (Bunn and Arthington, 2002).

Both in 2007-2012 and in 2015-2016 EFRs for the Mara River basin were established. The second EFR improved the recommendations from the first EFR, which allows these values to be applied to the WAP for the Mara River with increased confidence. In the EFAs it is generally assumed that the shape of the river stays the same, and water levels can be translated to discharges one to one. But for the Mara River, changes in river shape are seen in satellite images, by the change from anastomosing river to a single thread river and meander cut offs (Rowntree, 2016; Murunga, 2017). Therefore this assumption may not be valid, leading to limitations of an EFA.

1.2. Objective of this research

The objective of this research is to assess the influence of changes in flow regime on the long-term morphology for the Mara River Basin, in the perspective of the ecosystem habitat studies undertaken in the EFAs. In the Mara EFAs, the morphological aspect was assessed for representative sites of river reaches. In this study, the sites along the main stream of the Mara river are linked, and the sediment transport along a portion of the main stream is assessed. The area of interest is shown as the thick part of the river in Figure 1.1. To reach the objective, the morphology of the Mara River is assessed by the results of a field survey, the application of theory of the sediment transport principles and applying a numerical model with the aim to quantify the expected morphological processes.

The scope of the research is confined to the main stream of the Mara River and focusses on sediment transport processes and river topography changes in the longitudinal direction. The assessment is done for a stretch

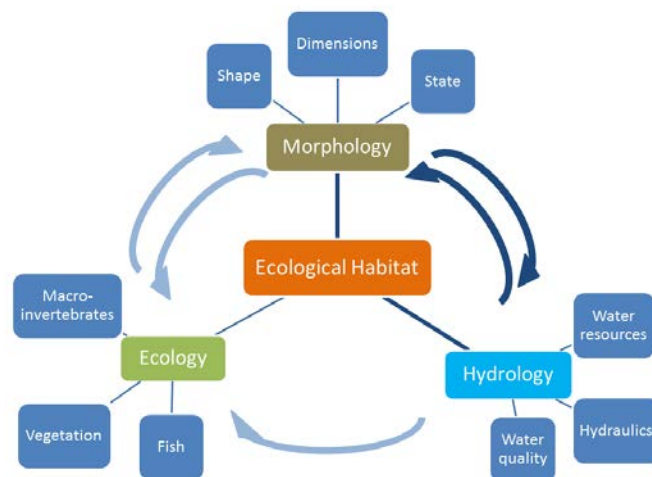


Figure 1.2: Disciplines within the assessment of the health of the riverine ecosystem (EFA). With this research focussing on the dark blue arrows, between hydrology and morphology.

of river of 200 km, beginning from the confluence of the tributaries in the north. Because of data limitations, the last 100 km of the Mara River, is not included in the analysis. The analysis is limited to reach scale 10-50 km, and only along the longitudinal direction of the river (1-dimension), because no specific details can be given on smaller scale, nor enough data is available to provide details to predict changes in the lateral direction of the river. The temporal extent of interest is 10-100 years, ranging from EFA-management cycles to a more interesting time scale for morphological processes. Aiming to quantify the morphological processes, this research will contribute to the understanding of the interdependent relations of the riverine ecosystem drivers and responses, which are important for restoration and management purposes in river basins.

1.3. Research questions

To reach the objective of this thesis, the following research question has been investigated:

"What is the influence of changes in flow regime on the long term topography and sediment transport, and what are the implications for EFR methodology for the Mara River?"

This main question is divided into the following sub questions:

1. What are the characteristic morphological processes taking place in the Mara River?
2. Is the topography of the river stable for the current situation?
3. What is the influence of the flow regime proposed by the Environmental Flow Recommendations on the long term morphology (sediment transport and bed topography) of the Mara River?
4. What are the implications of these outcomes for the EFR methodology?

1.4. Research approach

The approach taken for solving these questions is:

1. Literature review in order to understand the quantification of the morphological processes, link them to the ecological habitat, and to find the meaning of morphology for the EFA. Also the background of the Mara River basin will be explored here.
2. Field survey to collect data on morphology and hydraulics, and gain insight into the local processes at play. Representative sites were visited during high and low flows.

Information gathered from the literature review and field survey was used to characterize the river, and simplifications were made based on the characters of the river reaches. The proceeding steps were to make a:

3. Theoretical framework where the river can be represented by morphological mechanisms that lead to the quantification of future changes.
4. Numerical model to simulate and assess temporal changes of morphology.
5. Assessment of the impact of these outcomes on the EFA methodologies.

1.5. Readers guide

The first 4 chapters form the introduction of the research. Chapter 2 describes the theoretical background on morphology and the mathematics involved, together with a general background of EFAs and ecological habitat. Chapter 3 describes the available data from different sources which is used in this study.

Chapter 4 explains the methodology, divided into the methodology of the fieldwork, theoretical analysis and numerical model. The results are described in Chapter 5, focussing on the reference scenario and EFA scenarios.

The report concludes with a discussion to put the results in a broader perspective in Chapter 5, followed by the conclusions and recommendations about the gained insights in Chapter 6.

2

Background information

This background study covers the theory behind the hydrodynamics and sediment transport, including the formulas for quantifying the changes of bed levels. Also an elaboration of the ecological habitat, and a description of EFA methodologies are given, with the focus on the morphological part of the habitat assessments. In the last section of this chapter, the background of the river basin is discussed in more detail.

2.1. Hydrodynamics and Morphodynamics

The main natural function of rivers is to transport water and sediment downstream. Hydrodynamics describes all parameters that govern the flow of water through a medium which can be an open channel, or a closed conduit. The equations are based on mass and momentum balances, where the flow of water is driven by gravity. River morphodynamics is the study that describes the shape and structure of the landforms created by rivers. In the view of river engineering, the sediment transport, as part of the morphodynamics, is driven by the hydrodynamics and substrate properties. For sediment transport, the mass balance is used to describe the flow and storage of sediments. However, the capacity of the river to transport sediments is based on empirical and laboratory data, and therefore many assumptions are needed to determine the sediment transport in a natural river (Yang, 2002).

2.1.1. Hydrodynamics

In hydraulics, the Saint-Venant equations describe the flow of the water. Under the assumption that no mass is lost, the continuity equation and momentum equation are combined to describe the movement of water. In open water flow the equations are simplified to the Saint-Venant equations:

Continuity equation:

$$\frac{\delta A}{\delta t} + \frac{\delta(Au)}{\delta x} = 0; \quad (2.1)$$

Momentum equation:

$$\frac{\delta u}{\delta t} + u \frac{\delta u}{\delta x} + g \frac{\delta h}{\delta x} + \frac{gu^2}{C^2 h} = 0 \quad (2.2)$$

where;

A = Flow area (m^2)

u = Flow velocity (m/s)

g = Gravitational acceleration constant ($9.81 m/s^2$)

h = Water depth (m)

C = Chézy coefficient ($m^{\frac{1}{2}}$)

The hydraulic roughness (C) represents the coefficient that describes the friction exerted on the fluid, and plays an important role in the equation. Under uniform flow conditions, where the depth is constant in space, the friction ($\frac{gu^2}{C^2 h}$) and gravity term ($g \frac{\delta h}{\delta x}$) are in balance. The coefficient C used in the friction term, is the hydraulic roughness. The friction in a river is influenced by many factors such as bed material size which causes skin friction and relative roughness ($\frac{h}{D_{50}}$), but also bed forms, vegetation, obstructions, variations in

channel width and depth and curvature/sinuosity create extra friction. All these factors are captured in the hydraulic roughness, therefore it can be seen as a calibration parameter.

The hydraulic roughness can be represented in different ways, and can only be measured indirectly from field measurements by measuring all other parameters (slope, discharge, velocity). The Chézy coefficient and Manning roughness are discussed here.

In the above formula, the Chézy coefficient C is used to represent the hydraulic roughness. In steady, uniform flow, where no variations in time and space take place in the river, the water flow can be described by:

$$Q_w = AC\sqrt{Ri_b} \quad (2.3)$$

where;

Q_w = Discharge (m^3/s)

R = Hydraulic radius (m)

i_b = Bed slope (m/m)

With the assumption that bed slope in a river is equal to the water level slope (steady, uniform flow), the Chézy coefficient can be estimated from measurements of discharge and flow area:

$$C = \frac{Q}{A\sqrt{hi}} \quad (2.4)$$

Another representation is Manning's roughness coefficient. This roughness was derived from data collected on artificial and natural channels, with a range of shapes and boundary roughness (Gordon et al., 1993).

$$Q = \frac{1}{n} AR^{\frac{2}{3}} \sqrt{i} \quad (2.5)$$

where;

i = slope of the energy level; in uniform flow this is equal to the water level slope and bed slope i_b .

n = Manning's roughness coefficient.

Chow (1956) developed a reference table with values for the Manning roughness coefficient. These values vary from $0.025 \text{ s/m}^{\frac{1}{3}}$ for a smooth, clean, straight, channel without rifts or deep pools, and up to maximum $0.15 \text{ s/m}^{\frac{1}{3}}$ for the most resistant reach, weedy, with deep pools or flood ways with heavy stands of timber. Cowan, 1956 developed a method to determine the Manning roughness for a channel by taking into account the degree of irregularity, variation in cross section, obstruction, amount of vegetation and meandering, which contribute to the different friction aspects described before (Arcement and Schneider, 2017). Often the roughness of the channel is used as a calibration parameter in modelling, to fit the data with the modelled outcomes.

2.1.2. Morphodynamics

Morphodynamic changes can be categorized in changes that affect the river shape and changes that affect the rivers substrate also called sediment. **Plan form** changes originate from bank erosion and bank advance, for example in meandering rivers. The river can also adjust in vertical direction by changing its **topography** due to erosion and sedimentation processes. Indirectly the topography can also be changed by plan form changes. The third way of the river to adapt is via **sediment composition**. By selective transport the composition of the sediment can be changed by the fact that fine sediments will be picked up at a lower discharge rate than coarse sediments. Also hiding- and exposure effects are factors that influence the sediment composition, since coarser sediments covering fine sediments hamper the transport of the fines.

The amount of sediment being transported by the river is dependent on the river's capacity to transport sediment and is constrained by the amount of sediment available in the river (supply). The capacity of the river to transport incoming sediments is related to the hydro-dynamics, on the width, slope and flow velocity. Capacity limited rivers are mostly alluvial rivers where the available sediment is superfluous and can be picked up, depending on the capacity of the river to transport the sediments. For rivers that are under supplied of sediment, the flux is defined by the incoming sediment flux. This is often the case for bedrock controlled

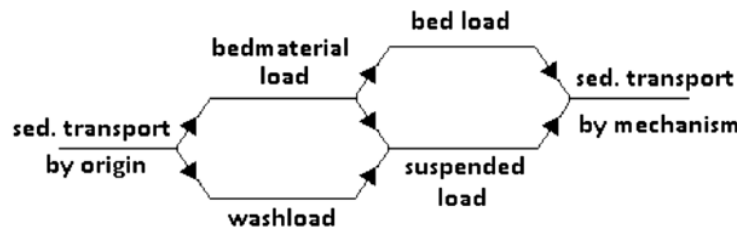


Figure 2.1: Classification of sediment by origin and mechanism (Jansen et al., 1979).

ivers.

The substrate of rivers can be bedrock or alluvial. In bedrock controlled rivers, the flow is confined within rock outcrops and channel morphology is determined by the relative strength and weakness of the bed material (rock) (Gordon et al., 1993). Bedrock is much less erodible, and thus the response of the bed in bedrock controlled rivers is much slower than alluvial rivers. Alluvial channels, containing sediment as substrate, are shaped by stream flow. The cross section, slope and size of the bed materials will be adjusted in such a way that they can transport the water and sediments coming from upstream most efficiently (Gordon et al., 1993).

Changes in plan form are expressed by for example meandering migrations or widening processes. This process of channel evolution in different environments is noted by researchers in fluvial geomorphology. The consequences of destabilisation by different natural and human-induced disturbances pass through a consistent, predictable, sequence of channel forms with time. These systematic temporal adjustments are collectively termed channel evolution, and permit interpretation of past and present channel processes, as well as prediction of future channel processes. (Darby and Simon, 1999; Simon and Hupp, 1986). Degradation in the form of erosion often occurs to a certain extent, after which channel widening occurs due to destabilization of channel banks by mass-wasting processes. Because of the initial flattening of the slope due to degradation and widening, the sediments will settle down causing sedimentation, because the sediment capacity goes down. Consequently the river fills up, but still widens. These steps are described by Simon and Hupp (Simon and Hupp, 1986). They also recognise the influence of re-establishment of woody vegetation on banks of incised channels, which induce the aggradation of the river banks.

2.1.3. Quantification of sediment fluxes

The first step in order to quantify sediment fluxes, is to determine which process of sediment transport is leading. Transport of sediment is discriminated by origin and by transport mechanism, see Figure 2.1. Different mechanisms are:

- Bed load transport, which is material rolling and hopping/saltating (caused by shear stresses on the bed material) while the sediments of the bed load are supported by the bed.
- Suspended load transport is defined as the load carried by the water column and transported downstream.
- Wash load transport, part of suspended load which will never interact with the bed, since it will always stay in suspension.

Sediment in the river can originate from the catchment, and ends up in the river for example by hillslope erosion, or it can originate from the river itself, by bank erosion or the river bed itself. Depending on the size of the sediments, it will end up as bedmaterial load, or washload in the river, and transported as bed load or suspended load mechanism.

Changes of the sediment transport in the longitudinal direction of the river results in changes in topography. This is described by the principle of conservation of mass (equation 2.6). $\frac{\delta A}{\delta t}$ is the storage over time, and $\frac{\delta S}{\delta x}$, represents the difference in ingoing and outgoing sediment flux in the control volume. For a stable river bed, where no erosion or degradation (storage = 0) is present over time, the ingoing sediment is equal to the outgoing sediment. This is illustrated in Figure 2.2.

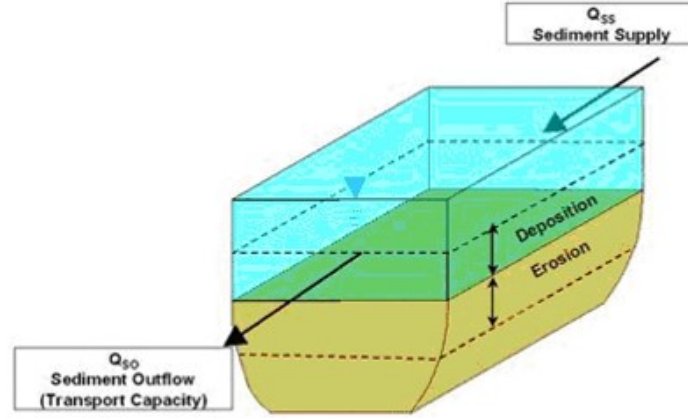


Figure 2.2: Sediment balance, erosion and deposition in a control volume

$$\frac{\delta A}{\delta t} + \frac{\delta S}{\delta x} = 0 \quad (2.6)$$

With $S = f(u)$ and $A = f(z)$, because the width stays constant, this results into the Exner principle:

$$\frac{\delta z}{\delta t} + \frac{dS}{du} \frac{\delta u}{\delta x} = 0 \quad (2.7)$$

The storage of sediments in a channel can be analysed on different time scales. Temporary sediments can be stored in the riverbed and bed forms, on the side of the cross section, for example due to discharge variation. On the longer term, obstructions are capable of storing sediments, such as logs, or bridges having their foundation in the river's cross section. At very long term, sediments are stored as floodplain deposits next to the macro-channel bed of the river, during floods overflowing the macro-channel banks (Gordon et al., 1993). At bedrock sections, the storage of fine sediments is located a bit higher up the cross section, and is only activated during high flows.

The movement of bed load material can be described as stochastic processes, since particles can be taken up to move in suspension, they can roll, slide or hop or they can stay put (Gordon et al., 1993). This all depends on the bed shear stress (τ_b) and on the structure of the sediments. Bed shear stress is the result of fluid forces acting on the sediment particle as a result of skin friction and pressure forces (which cause drag and lift forces). For gravel bed rivers, selective transport, leading to a change in sediment composition, can be significant (Rijn, 1993). The sediment transport fluxes for rivers containing uniform sized bed load material are described by empirical transport formulas for suspended load, bed load, or both. Generally these formulas contain the gravity-acceleration constant (g), fluid characteristics (ρ , v), sediment characteristics (ρ_s , D) and other parameters describing the influence of the flow (τ_b). For alluvial rivers the sediment transport formulas can be simplified to:

$$Q_s = B m u_e^n \quad (2.8)$$

where,

Q_s = sediment transport [m^3/s]

m = parameter depending on the sediment characteristics and channel roughness [$\text{m}^{1-n}/\text{s}^{1-n}$]

n = exponent accounting for the degree of non-linearity of the transport equation [-]

B = width of the channel [m]

u_e = uniform flow velocity [m/s]

One specific sediment transport formula is the Engelund-Hanssen transport formula. This is a semi-empirical formula, verified by experimental data, which takes into account transport of both suspended and bed load

material. As can be seen in the formula (Equation 2.10 and 2.11). The sediment flux is dependent on the flow velocity which means that as long as the water is in movement, there will also be sediment transport. Engelund Hanssen:

$$m = \frac{0.05}{C^3 \Delta^2 D_{50} \sqrt{g}} \quad (2.9)$$

Where:

D_{50} = median grain size of representative sediment (m)

Δ = relative density of sediment (for sand; 1.65) [-]

And by substituting Equation 2.9 into Equation 2.8 Q_s becomes:

$$Q_s = B \frac{0.05}{C^3 \Delta^2 D_{50} \sqrt{g}} u_e^n \quad (2.10)$$

Where the u_e for uniform flow from Equation 2.3 leads to the formulation of sediment flux independent of h and u :

$$Q_s = i^{\frac{5}{3}} Q^{\frac{5}{3}} B^{-\frac{2}{3}} C^{\frac{1}{3}} \frac{0.05}{\Delta^2 D_{50} \sqrt{g}} \quad (2.11)$$

The formula is especially applicable for the total load of relatively fine material, in which the suspended load plays a dominant role, so in cases where $\frac{w_s}{u_*} < 1$. The formula has been validated for streams with bed sediment sizes where $0.19mm < D_{50} < 0.93mm$ and conditions of mobility are in the range of $0.07 < \Theta < 6$. The Shields parameter, Θ , is a measure of mobility of the sediment. It is the ratio of bed shear stress exerted by the flow versus gravity on a particle. The threshold of motion depends on the critical value of the Shields parameter as a function of the flow conditions defined by Re_* , and visualised in the Shields diagram (Jansen et al., 1979). Where $Re_* = \frac{u_* D}{\nu}$, and ν is the kinematic viscosity.

$$\Theta = \frac{u_*^2}{\Delta g D} \quad (2.12)$$

Another sediment transport formula is the Meyer-Peter and Müller transport formula. This equation is a purely empirical formula, relating the Shields parameter Θ with the discharge.

Meyer-Peter Müller:

$$Q_s = 8 * D_m^{3/2} * \sqrt{g * \Delta} (\mu * \Theta - 0.0047)^{3/2} \quad (2.13)$$

From equation 2.13 it can be seen that the Shields parameter first has to overcome a critical value of 0.0047. Since the formula is focussed on the mechanism to overcome incipient motion, one can already conclude that the formula is only applicable for bed material load transport. The formula is empirically validated for river beds with sediment diameter bigger than $0.4mm$, and for situations where the fall velocity overcomes the shear velocity ($\frac{w_s}{u_*} > 1$), which also points out the focus is on bed load.

Rivers in equilibrium An equilibrium in morphodynamic state exists when the storage within a reach does not change, thus when all incoming sediments are transported downstream and the bed level does not change in time. In this case the parameters of the rivers geometry are providing enough capacity to transport the incoming sediments. For an alluvial river in equilibrium, the sediment transport is equal to the sediment transport capacity. When all parameters of the sediment transport equation are known, discharge, width, sediment size, roughness and slope, the sediment transport can thus be calculated for the equilibrium situation. Changes within these parameters drive the system to a new equilibrium state. The analysis of the equilibrium conditions in this section is based on the assumption of an alluvial river, where the sediment transport formula of Engelund-Hansen is valid to apply. By applying Equation 2.11 for both equilibrium situations, the new equilibrium situation can be calculated. For the equilibrium slope, the equation results in Equation 2.16.

Since the discharge in the Equation 2.16 is a constant discharge, a representative discharge has to be chosen from the discharge record. Since the transport formula of Engelund-Hansen includes the velocity to the power 5, it can be seen that high discharges are very important for the sediment transport. Therefore, an average discharge is not good to choose. In Equation 2.14, it can be seen how a varying discharge is taken into account to calculate the sediment transport (Crosato, 2014). In Equation 2.14 the discharge is taken monthly, but the same can be done for daily discharge records, see Equation 2.15.

$$Q_s = \frac{mC^{(\frac{2n}{3})}i^{(\frac{n}{3})}}{B^{(\frac{n}{3}-1)}} \sum_{k=1} 12 \frac{1}{12} Q_{w,k}^{(n/3)} \quad (2.14)$$

$$Q_{representative} = \sum p(Q_{w,k}) * Q_{w,k}^{(n/3)} \quad (2.15)$$

Where $Q_{w,k}$ is the discharge for month k .

And $p(Q)$ the probability distribution is for Q_w .

$$\frac{i_1}{i_0} = \frac{Q_0}{Q_0 - \Delta Q} \quad (2.16)$$

With Q_0 and i_0 the discharge and slope at $t = 0$;

ΔQ the difference between discharges at $t = 0$ and $t = \text{equilibrium}$, and

i_1 the slope at the equilibrium situation.

While the water surface responds instantaneously to perturbations, resulting in backwater curves, morphological adjustments by erosion and deposition of bed load sediments due to changes in sediment transport capacity often take much more time (+100 years). The time scale of adjustment from the one equilibrium state to the other equilibrium state can be approximated by Equation 2.17 (Jansen et al., 1979). The formula describes the time until half of the magnitude of the perturbation has occurred ($T_{0.5}$) at a certain distance from the location where the perturbation is initiated ($L_{0.5}$). The formula only gives an approximation of the time scale, and does not give insight into the temporal behaviour of the bed response on a smaller time scale.

$$T_{0.5} = \frac{3i_b L_{0.5}^2}{bq_s} \quad (2.17)$$

2.1.4. Morphodynamic models

The analytical formulas describing the flow and sediment transport can be applied in a numerical framework. In such a framework, the discharge, elevation of bed and boundary flows at different time steps are defined, giving insight in the temporal development of changes in sediment transport and bed level changes. Since the sediment transport equations are coupled to the Saint-Venant equations, these equations need to be solved simultaneously, iteratively for each small control volume. In the previous section, for the analytical approach above, the formulas are linearised, and give the characteristic time and spatial scales. Another way to calculate the changes of bed level and sediment transport is to divide the river into grid cells, and calculate for each grid cell the hydrodynamic and morphodynamic equations iteratively. This results in a numerical model.

The numerical model requires data which define all initial conditions and boundary conditions and states (shape, depth, discharge). With these, the equations calculate the responses to disturbances from outside. The equations (and thus input data) can be posed for solving the 1, 2 or 3 dimensional solution space. The mechanism of sediment transport is described with the sediment transport formula and the Exner principle. The numerical models are dependent on the boundary conditions and initial conditions imposed in the framework. The advantage of numerical models is that it shows the transient response of disturbances, and that several disturbances can be combined. Disadvantage is that errors are imposed by boundary and initial inputs are progressing throughout the rest of the model space. This can be avoided by choosing wisely the time scales and model extent with respect to the area of interest (see Figure 2.5).

2.2. Ecological habitat

King et al., 2008 describe local hydraulics and channel morphology as the primary determinants of the availability of ecological habitat, which in turn, is the major determinant of ecosystem functioning. System drivers in the river ecology are hydrology, geomorphology and physio-chemical conditions. The responses are observed in fish, riparian vegetation and macro-invertebrates, mainly in their community distributions (Rowntree, 2013). This approach is based on the assumption that biota need certain conditions in the ecological habitat for survival, and that the population distributions give insight into the responses of these biota to the system drivers. An example for the description of ecological habitat is visualised in Figure 2.6.

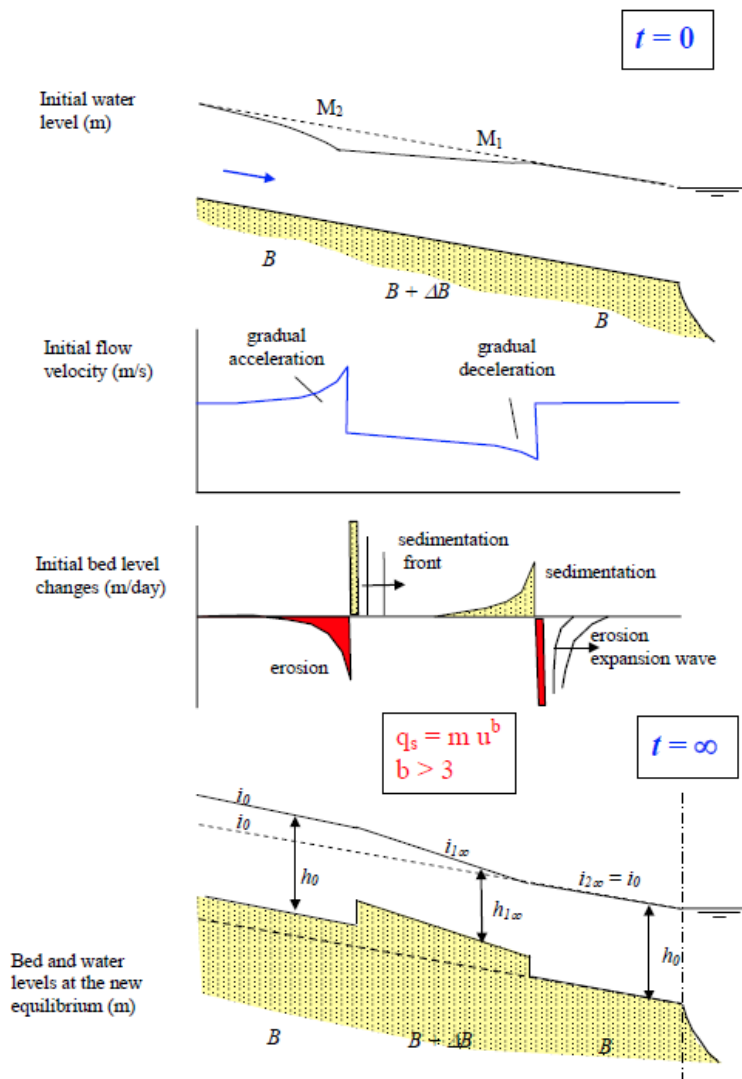


Figure 2.3: Morphological adaptations for widening of a river reach (Crosato, 2014).

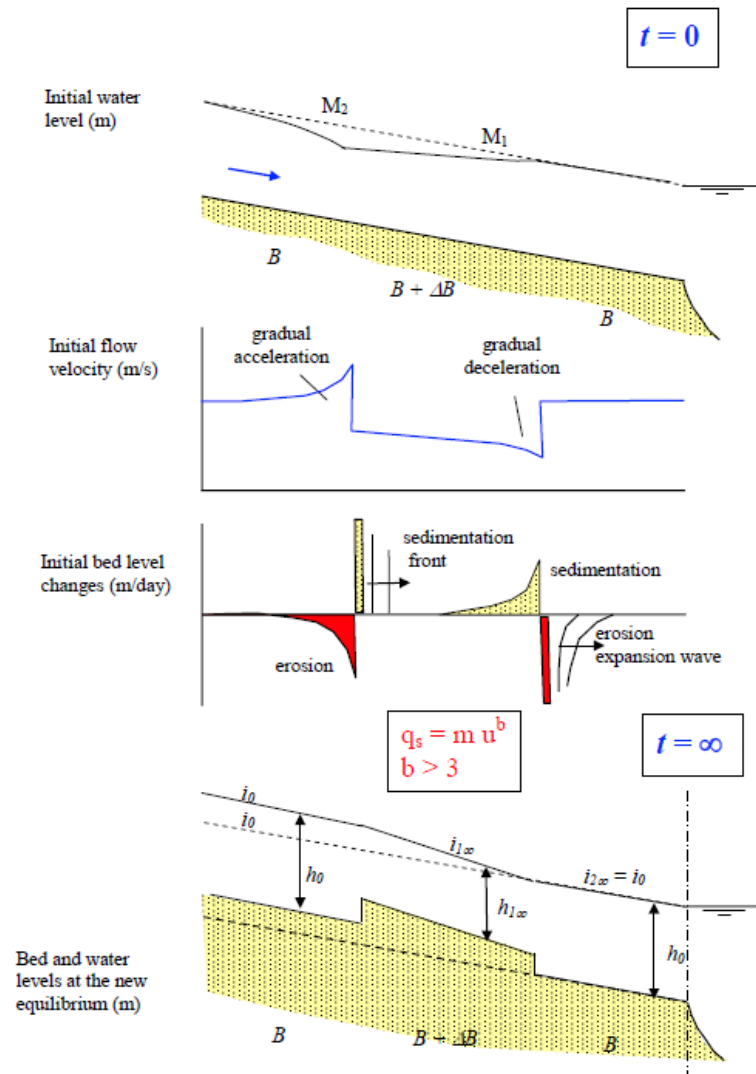


Figure 2.4: Drivers for sediment transport when water is withdrawn from the river (Crosato, 2014).

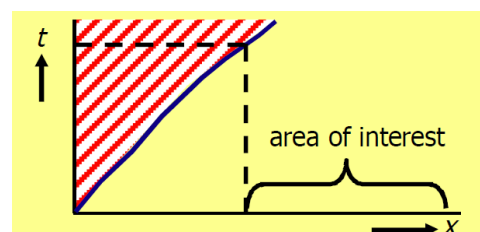


Figure 2.5: Propagation of errors made in the boundary conditions (the parameters described at $x=0$) travel through the model. The area of interest and the extend of the model should be chosen in a way that these boundary conditions do not influencing the area of interest.

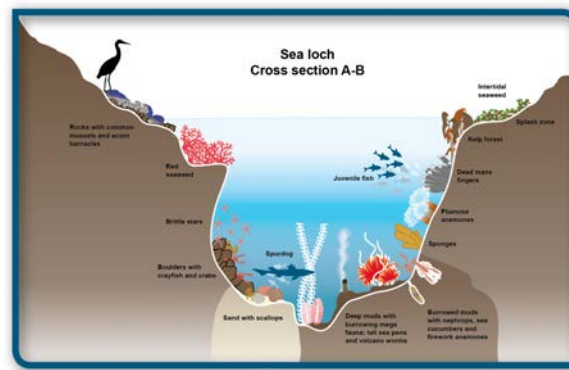


Figure 2.6: Example of ecological habitat in a Sea Loch in Scotland. (Image from website of Scotland's Environment <http://www.environment.scotland.gov.uk/get-informed/water/rivers-and-lochs/>)

Fish communities, as responders, are dependent on changes and variations of velocity, depth, width of the wetted area, which determine where the fish can live well. The substrate condition is also an important driver, as that influences the suitability for spawning habitat and egg incubation. Macro-invertebrates are dependent on the substrate conditions, including presence of woody debris, as they find their food, as bio-films and algae, here. During flood events, the river should provide shelter for both fish and macro-invertebrates, in order to not wash them away. Variability in the cross section is therefore important, where flood benches and flood plains can provide slow flowing areas during flood events. For the survival of vegetation the water availability in the rooting zone is important as well as the opportunity to re-juvenile. These factors are dependent of the combination and stability of substrate, water availability and flow velocity.

Factors that change the shape of the habitat are mainly flow velocity, sediment transport, and sediment supply. Important factors of the morphology are connectivity, (for providing shelter and providing the floodplains of new sediments), channel stability (for vegetation recruitment and spawning habitat), and lastly sediment supply (for sustaining the vegetation and fish spawning habitat). To maintain these aspects, generally three flows can be distinguished to maintain the rivers character and shape (Rowntree, 2013).

1. Thalweg flows. The minimum flows that sustain fluvial processes, supporting minimal sediment transport and providing water in the root zone of plants.
2. Channel maintenance floods. Flows that overflow flood benches, supporting vegetation growth on banks, stabilizing the channel and refreshing the bed sediments.
3. Channel forming floods. These are important to maintain geometry and longitudinal connectivity by scouring obstructions and cleaning the river bed. And secondly these flows, reaching the floodplain, replenish the floodplain with sediment supply and maintain lateral connectivity with the floodplain.

2.3. Environmental Flow Assessments

The EFA aims to identify the water demand required to maintain specified valued features of the river ecosystem, and quantifies this demand. When anthropogenic intervention in the river is present, for example due to construction of a dam, or other discharge regulating constructions, the health of the ecosystem can be protected by implementing and managing the water resources as recommended in the EFR. Other situations that can benefit from implementing an EFR are degraded rivers, or in situations when enhancing the survival chances of threatened fish species is desirable.

Many methodologies have been developed for establishing an EFR. These are categorised in hydrology based, hydraulic rating, habitat simulation or holistic methods. Respectively these methods demand more and more data, starting by hydrological records of flow, river width and wetted perimeter, to data where hydrological, hydraulic and biological responses are integrated. Holistic methods consider the complete ecosystem as integrated system, where geomorphological, water quality, social, and ecological (fish, vegetation, macro-invertebrates) elements are distinguished, see Figure 1.2.

Holistic methods recognise the importance of variable flow regime, where timing, frequency and duration of

flood pulses are key aspects of the assessment, as they base the modified flow regime on a month by month interval, supporting target species or features from each element. Applying the holistic method can be achieved by following the Building Block Framework (King et al., 2008). In this framework, a desktop study (pre-field study), field study and a workshop (post-field study) are undertaken by a team of specialists from each element in the ecological habitat to integrate all elements.

Field survey

The objective of the field survey is to determine the percentage of suitable habitat for target species at representative sites along the river. Representative sites for the reach are found by a literature study and a reconnaissance field trip. Within the chosen site, representative transects need to be set up, which is the basis of the survey. All specialists collect data of the river habitat conditions and biota that live there along these transects. It is important to find habitat diversity, sensitivity to flow changes, and the corresponding critical situations, for target species (species most critical for survival or representative for ecosystem health). A critical flow transect is where the flow is hampered first when discharges are reduced. Therefore riffles are good critical flow sites since they will be the first to be exposed when discharge gets smaller (Muthike et al., 2007b).

Workshop

In the workshop, the minimum habitat coverage to maintain habitat diversity and channel morphology is determined with help of the hydraulic modelling. This is done taking into account the Present Ecological State (PES), and the direction of change and the desired ecological state. The last one has to be defined together with stakeholders and Water Resources Management Authority. Many interrelated processes need to be considered that operate over a range of time scales. Ecologists are looking for thresholds for a certain coverage of area and habitat diversity, which when overruled, will degrade the system to an undesirable state. These are called Thresholds of Potential Concern. For the morphological discipline, diversity of habitats shape and substrate, habitat stability and habitat connectivity are important factors that need to be maintained in future conditions. In the Geomorphologic Assessment Index method (Rowntree, 2013) this is done by describing the current state of the river morphology and the drivers of change by classifying, ranking and weighing geomorphological features and anthropogenic impacts. Hereby the geomorphological discipline should also provide a catchment wide view, with long-term time scale and also support the other disciplines to connect to this bigger time scale (King et al., 2008).

In the last step before deriving the specific flows, the habitat conditions available for target species are linked to hydraulic parameters. The hydraulic specialist models the flow conditions as function of different discharges with habitat models. Output parameters of these models represent hydraulic habitat conditions in depth, velocity and wetted perimeter, and relate these parameters to the discharge. Models used for this purpose are for example HABFLO and PHABSIM. HABFLO is a 1-dimensional hydraulic habitat model, which translates flow velocity and depth to percentages of coverage in the cross section, which consequently is linked to the needs for fish species. PHABSIM calculates the quantity and quality of the available habitat for each species by indicating the Weighted Usable Area (WUA).

In the workshop, the minimum habitat coverage to maintain habitat diversity and channel morphology is determined for low- and high-flow months by the whole team of specialists. These are translated to minimum flows based on the hydraulic modelling. Many interrelated processes need to be considered that operate over a range of time scales.

2.4. Mara River Basin

2.4.1. Physical features and natural processes

Major faulting and volcanic activism defined the physical boundaries of the Mara-Serengeti ecosystem (Peters et al., 2008). The Mau Escarpment in the north and the Siria Escarpment are these natural boundaries defining the extent and geology of the Mara River Basin. The geology is very heterogeneous in the basin, as can be seen in Figure 2.7. Basalt, granite and gneiss alternate each other. Also sedimentary rock (sandstone) is found just downstream of Emarti and in the wetland in Tanzania. The Siria escarpment can be well distinguished in blue, representing quartzite, which is resistant to erosion.

In the North the Mau Escarpment provides a mountainous region, with an altitude of maximum 3065 m. Two tributaries from this region feed the main stream Mara River, which enters vast savannah plains, bounded by

the Loita and Sienna Hills in the East and the Siria Escarpment in the west. After flowing through the Massai Mara, and the Serengeti in Tanzania, the river reaches the Mara Swamp at an altitude of 1170 m, the river flows out to Lake Victoria at 1135 m above national datum.

Due to its location in the inter-tropical convergence zone (ITCZ), the Mara River Basin experiences a biannual rainy season, and the climate is semi-arid to arid. The hydrology is therefore characterised by the biannual rainy season. Long rains hit the basin in March-April-May. In October-November-December short rains occur. Spatially the rainfall in the Mara Basin is highly heterogeneous, largest in the north, around the Mau escarpment, and declines to south, where elevation drops. Long-term annual precipitation averages for the Mara ranged from nearly 1500 mm on the Mau Escarpment to 600 mm per year high up in the Sand tributary and 800mm at the river's mouth (Mcclain et al., 2013). The protected Mau forests in the north act like a water tower for the river basin, storing the water and discharging via the tributaries Amala and Nyangores water to the main stem Mara river, ensuring a perennial character. The Talek and Sand tributaries, originating from the Loita Plains feed the river only seasonally and flash floods are common events in these tributaries.

The main land use in the basin can be classified as agriculture, range lands, savannah and reserve. The upper Mara, along the Nyangores and Amala river, is dominated by small-holder farming and encroachment of the Mau forest. At Emarti, where the two tributaries meet, agriculture in the form of large-scale irrigation using pivots can be seen. More to the south, conservancies start, where land use is regulated. Life stock is actively grazing in these range lands. Downstream of Kichwa Tempo the Masai Mara starts, where the savannah with high grass and shrub starts. The Masai Mara, being an unfenced national reserve, experiences livestock grazing at the boundaries of the park, which is clear by the decrease of the height of the grass here. The border of Serengeti National Park is well distinguished from satellite images. Just downstream of the border, small-scale agriculture pattern is visible. Some agricultural plots are extended onto the floodplain of the river, benefiting fertile soil, but risking inundation during high rainfall events. Downstream of Mara Mines, the river starts to meander more and the main river gets narrower, and diverts. Here the river enters the wetland, where the flow of water slows down and sediments settle down.

From these land uses, also the actors depending on the water resources become evident. Firstly there is the human population in the area, who wash, drink and cook with the river water. The population is growing with .. percent. Secondly, both in Kenya and in Tanzania, smallholder agriculture (for basic human needs) and large-scale agricultural farms are found which need water for their crops. Thirdly, the wildlife in the eastern horn of Africa, wildebeest are dependent on the water resources as they follow the fresh grasses and migrate from the Serengeti to the Massai Mara. The wildlife itself is an important stakeholder, but both Kenya and Tanzania also profit a lot through the economy it creates bringing tourists in the parks. This tourist economy is again also dependent on the water resources in the basin to comfort the tourists. Lastly, the wetland near Lake Victoria is dependent on the water from upstream, quality and fish habitat.

2.4.2. Developments in the basin

Encroachment of the Mau forest (Munguti, 2014, Mati et al., 2008) is affecting the regions around it. Since the Mara River finds its origins in this forest, the basin is expected to be dependent on the forest. From 1973-2000 there has been degradation of land use in the area, namely a reduction of 52% of the area of rangelands and 32% of the area of forests (Mati et al., 2008). Mati et al. also link these reductions to a change in hydrology, increased peak flows by 7% and soil erosion building up silt in the Mara wetland. The hydrological regime is expected to change, having higher peak flows due to less storage in the upper catchment and lower low flows due to more abstractions of agricultural farmers and domestic users (Mati et al., 2008, Mango et al., 2011, Defersha et al., 2012). They state that due to less forests in the upper catchment, there is less storage in the soil to store water during high flows, resulting in a larger flux of overland flow, and due to a different vegetation cover, more sediments would be taken to the river. However, Dutton et al., 2013 and Hulsman, 2015 found by respectively sediment fingerprinting and a modelling study, that the suspended sediments mainly come from the Talek and Sand regions.

Secondly population growth is expected to increase through the 21st century. For Kenya and Tanzania the general population growth is 2.4 and 2.5% per year, such kind of growth is putting more pressure on the water resources (Hoffman, 2007). At the same time, it is then also likely that agricultural area, in the sense of

small-scale farming, will grow (Dessu et al., 2014). Also, the population growth will impose more rural area and roads, changing the drainage characters of the land. Lastly, the competition between humans, livestock and wildlife will continue.

The Kenyan and Tanzanian governments are making plans to construct reservoir dams in the Mara River, with the aim to increase water security and support economic development (Nile Basin Initiative (NBI), 2014). Consequences of such dams could be that the discharge in the high season will be decreased, while the discharges during the low flow season would increase when optimum hydropower conditions are maintained. The environmental consequences are considered in the feasibility studies, but mainly the feasibility reports (Nile Basin Initiative (NBI), 2014) are focussed on the economical values of the dams. The performed EFA studies are focussed on the health of the ecosystem, and give the input to be able to assess the feasibility of the dams with respect to the environment.

2.4.3. Morphological research in the basin

Relevant literature about the morphology of the river comes from Hulsman, 2015. She concluded that coarse sediment mainly originates from the river itself, since the density of gullies providing coarse sediment to the river would not be enough to supply the amount of sediment needed for the dynamics of the river. The measure for the dynamics of the river was estimated by comparing Digital Elevation Model (DEM) from 1996 with 2014. Dutton, 2012 noted another significant effect on the rivers' morphology, which is the walking and grazing of hippos. He considers them as the natural engineers of morphology, engineering pools as they deepen them by walking and living in them, and engineering the riverbanks when they walk from the river to the terrace, creating gullies along the steep river banks which increase the connectivity of floodplains/terraces with the river and create flood benches along these steep banks.

Satellite imagery from Google Earth provides evidence to assume that the river has moved from an anastomosing character to a single thread river (Rowntree, 2016). Rowntree mentions two hypothesis for the initial cause of the incision and straightening of the river, both having a natural cause. The incision stems from a time when the stream power was increased, which she thinks can be caused by a hydrological shift or a tectonic shift, in accordance with literature about incised channels (Darby and Simon, 1999). A shift in hydrology can be justified by literature, where after the Little Ice Age (1300-1800) where a cold and dry period, a period of drought followed (Nicholson et al., 2000). Degradation of riparian vegetation, reduces the rivers resilience to floods. In the period of 1876-1878, the Lake Victoria levels rose enormously, correlating with El Niño like wet and warm period. This shift in discharge, from low discharge with low stream power, to high discharge with a lot of capacity to transport materials, and in the same time a channel which has less roughness due to reduction of riparian vegetation, and less cohesive sediments because of this, may lie at the root of the cause for incision.

The second hypotheses of Rowntree is that a tectonic uplift of the Siria fault, causing part of the river to steepen, could have been the initial cause which has led to an increase of stream power needed for the incision to start. Since little is known about the dynamics of the Siria fault, the time scale for this process is very uncertain.

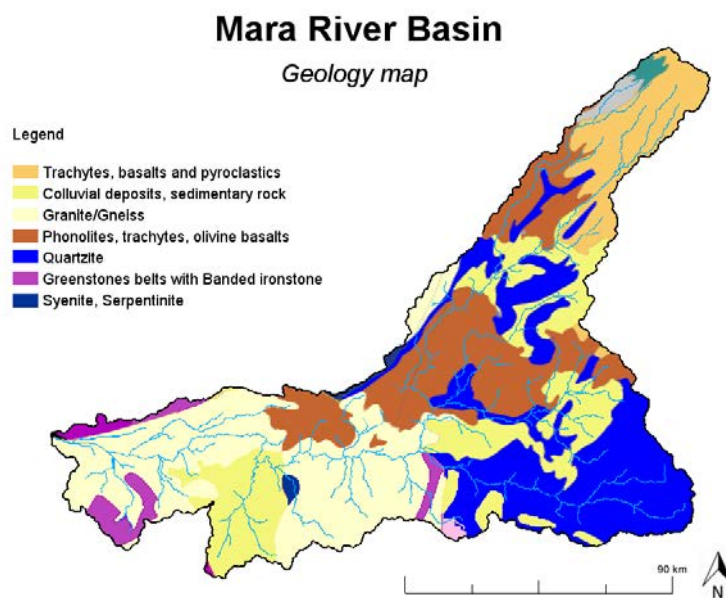


Figure 2.7: Bedrock map of the Mara River basin (source: OneGeography website, data from Southern and eastern African Mineral Centre (SEAMIC)).

3

Data

In this chapter, the data used and obtained in the research are summarized. The data are categorised by the group that acquired them. Water Resources Management Authority of Lake Victoria South River Basin Management has discharge and water level records for six sites in the Mara River Basin. These data are used for hydrological modelling purposes by Hulsman, who modelled water levels and discharges of all subbasins in the Mara Basin based on rainfall records and water level records (see Figure 3.1).

Several field surveys have been undertaken, and data available from these surveys are also used in this research. The first survey of which the data are available was the field survey, in the Kenyan part of the Mara Basin by a group of six Dutch students. Secondly, the starter-document of the hydraulic survey of the EFA of 2012 is available, Ndomba, P.M. and Mtamba, 2012 containing the data of the hydraulic survey. In Muthike et al., 2007b a summary of all starter-documents is given, including the hydraulic and morphologic survey. Thirdly data of other specialists reports of the EFA survey from 2015-2016 is used for comparison.

Lastly, satellite data are used for characterising the river. All these data are discussed in the sections of this chapter.

3.1. WRMA data

The WRMA of Lake Victoria South Basin in Kenya records water levels daily at six sites in the Mara Basin, of which 2 are along the main stem. The oldest record ranges from 1955, but the data have gaps of years/months. The Emarti gauging station (upstream in the main stem Mara) is only running since 2012. The data are collected by local agents that measure the staff gauge twice per day. Every month a WRMA officer collects these records, and measures the discharge and water level stage, to construct the rating curve. The data are transferred to the Kisumu office of WRMA, where the database is located. In Tanzania, the process is expected to be the same for recording water levels at Mara Mines gauging station. These records have been acquired via WRMA and the MamaSe project. In total the data of 3 water level gauging stations along the main stem Mara are used; Mara Emarti station (1LA06), Mara Kichwa Tempo (1LA04) and Mara Mines (5H2).

The rating curve created by a series of monthly measured discharges and their corresponding water levels, which are converted to a rating curve for all discharges in between and outside the measurements (interpolated and extrapolated). In this way, the Kisumu office has both a water level and a discharge record of the gauging stations. For the upper tributaries Hulsman, 2015 noted that the rating curve at Amala has changed several times in history, this can be caused by reconstruction of the gauges after high flows or vandalism. At Nyangores the rating curve is quite stable. The Talek and Sand gauging stations have been recording from 2012. Not much data is collected for the rating curve since discharge measurements in these tributaries is difficult due to the flashy character. The Emarti rating curve is also recently established, as the station operates since 2012. Discharges measured at Kichwa Tempo measurements unfortunately lack between 1990-2012. Also the rating curve data collected are not stable enough to transform water level to a reliable discharge.

For Mara Mines, data are analysed by both Hulsman, 2015 and Ndomba, P.M. and Mtamba, 2012. Both concluded that the rating curve is adjusted in time. Hulsman concludes that discharges are less reliable than water levels and continues modelling with the last ones. Ndomba created a best fit rating curve based on PC1 and PCR models can be used as average rating curve for Mara Mines (5H2), but also concluded that it is possible that the cross section has changed over time.



Figure 3.1: Subcatchments which define the modelled discharge records from Hulsman, 2015.

The discharge records used for the analysis in this research rely on the modelling results of Hulsman, 2015 from 1970-1993. The monthly average data comply with the monthly average data from the WRMA discharge records from Emarti and Mara Mines. The difference is that the modelled data give insight into the magnitude and timings of the inflows into the basin.

The discharge data are used as input for the hydraulic forcing of the 1-dimensional sediment transport model.

3.2. Field survey data obtained by the Dutch6 group 2014

The Dutch6 group (a group of 6 students from The Netherlands) has set up an experimental hydro and meteorological measuring network. They cooperated with Chris Dutton (Dutton, 2012) in Sept - Oct 2014. For the hydraulic sites they conducted discharge and cross section measurements, and set up water level loggers and time-lapse cameras (Rey et al. 2015). The discharge was measured with the RiverSurveyor (Acoustic Doppler Current Profiler (ADCP) on a unmanned boat). Cross section measurements were done by measurement tape and laser distance meter. The slope was, where possible, measured with a dumpy level. Of all 11 sites they visited in the river basin, 5 sites along the main stem Mara were included, namely Emarti, Mara Kichwa Tempo, Govenors Camp, Serena Pumphouse, and Purungat Bridge. The data are well documented, and also access to the RiverSurveyor files has been provided, as well as pictures which give qualitative information about the state of the banks, terrace and main channel. The hydraulic field data and the pictures of sites are used for comparison and characterisation of the river.

3.3. 2007-2012 EFA field survey data

Previous EFA surveys were carried out in March and July 2007, on the Kenyan site of the basin, and in February and March 2012 on the Lower Mara River at the Tanzanian site of the basin. The field assessments undertaken included the physical indicators hydrology, hydraulics, geomorphology and water quality, as well as the biological indicators riparian vegetation, aquatic macro invertebrates and fish. Also participatory surveys were conducted, identifying social indicators as the available river resources, primary resource users, relative importance and seasonal availability of these resources. In total 6 sites were visited, of which 4 were along the

main stream of the Mara, which are of interest in this research. These were Mara Safari Club, Mara Purungat Bridge, Mara Kogatende and Mara Mines. For all sites, 4 cross sections perpendicular to the flow were surveyed within 70-150 meters along the river.

The geometrical survey included an assessment of meso-habitat, survey of bed elevation and cross section and survey control points. The cross section measurements were done with a dumpy level, staff and 100 m tape measure. The bed slope was derived from the thalweg depths in the cross sections. The flow and discharge measurements were carried out along the transects using a Flow Tracker Hand held Acoustic Doppler Velocity meter (ADV), or when impossible to cross the river, by the floating method (Kogatende and Mara Mines).

The geomorphological survey sampled sediment in different habitats, pool and riffles, based on more than one transect of pool or riffles. A clast analysis was done, together with an assessment of stability of the banks, bed and flood benches. Sediment sampling on the boat-traversed transects was however restricted by water depth, strength of currents and wildlife. Benchmarks were placed at the cross sections to relocate them at the high flow survey.

The EFA field data from 2007-2012 are used for comparison and to provide information about sites that could not be visited during the field survey for this research.

3.4. 2015-2016 EFA field survey data

Since this research was partly cooperated with the EFA field survey of 2015-2016, the data of the other disciplines (vegetation, fish and macro-invertebrate reports (MacKenzie, 2016, O'Brien, 2016, Masese, 2016)) are also used for comparison and background information. Of course the data from the field surveys itself will be further elaborated in the rest of the report and Appendix C.

The scenarios for future discharges are based on the EFR of the 2016 report. The Amala and Nyangores site are added up to form the inflow from upstream, at Emarti. It is assumed that the flows at those two sites are also recommended for the Emarti site, of which no recommendation is done, but comparison is made with the EFR of 2012. The Purungat site provides the flows for reach 3, and the Mara Mines site provides the flows for reach 4.

3.5. Satellite data

The elevation profile of the river was obtained from NASA STRM3, 90 m resolution data set, after tracking the river in Google Earth. This gave also the sinuosity ratio for different reaches. The Google Earth imagery also provides insights into the river features along the banks, or instream. Based upon the slope, confinement and probably bedmaterial, the Buffington-Montgomery index (Montgomery and Buffington, 1997) is given. These data are used for the Desktop Study, which brings together data analysed from the desktop prior to going into the field.

Table 3.1: Data that is collected from literature. (MB = Mara Beef; EM = Emarti; SC = Safari Club; MKT = Mara Kichwa Tempo; SP = Serena Pumphouse; GC = Govenors Camp; PB = Purungat Bridge; KT = Kogatende; MM = Mara Mines)

Data	Specification	Source
Discharge & Velocity profiles	Monthly measured (ADCP) @EM, MKT, PB	WRMA
	Measured in 2014 (ADCP) @ SP, GC	Rey et al., 2015
	Once measured (Floating method, ADCP) @KT, MM (2012) @SC, PB (2007)	Ndomba, P.M. and Mtamba, 2012
Cross section	Laser distance meter @ EM, SP, PB	Rey et al., 2015
	Dumpy level, measure tape @ SC, PB, KT, MM	Ndomba, P.M. and Mtamba, 2012
Slope	Dumpy level @ SC, KT, MM	Ndomba, P.M. and Mtamba, 2012
Water level	Daily measured	WRMA
	Modelled	Hulsman
Sediment analysis	Percentage coverage of clast size @SC,PB	Muthike et al., 2007 <i>b</i>
Suspended Sediment	Events	Dutton, 2012
	Events	Kiragu, 2009
	Modelled	Hulsman, 2015
Topographic	STRM3 (90m resolution)	NASA
	Elevation profile Mara in Kenya	Dutton, 2012
	Elevation profile Mara in Tanzania	Ndomba, P.M. and Mtamba, 2012

Table 3.2: Data collected in the field during the 2015-2016 field survey (* = no bed sediment collected; MB = Mara Beef; EM = Emarti; MKT = Mara Kichwa Tempo; PB = Purungat Bridge; MM = Mara Mines)

Field survey data	Measurement device	Locations
Discharge & velocity profiles	RiverSurveyor	MB, EM, MKT, PB, MM
Cross sectional profiles	Total station and DGPS	MB, EM, MKT, PB, MM
Habitat mapping	DGPS	MB, PB
Slope	Total station and DGPS	MB, EM, MKT, PB, MM
Bed and bank sediment size	Sand ruler	MB, EM*, MKT*, PB, MM

4

Methodology

The aim of this research is to combine the EFA, a site specific assessments, to an assessment of a large reach of the main stream of the Mara river, focussing on the link between morphology and hydrology and the consequences of morphological changes to the ecological habitat. Generally, assessments of a system can be categorised in spatial and temporal detail level. This is illustrated in Figure 4.1. In this research, the analyses focussed on both local and short term, being low-flow and high-flow, detail level, as well as river scale, long term and coarse level. The large-scale and long-term assessment consist of both a desktop study and 1D sediment transport processes by using principles of river engineering. The aim is to translate the results of this analysis to possible consequences for the ecological habitat. The local, detailed level of the assessment was done in cooperation with the EFA specialist team during the EFA field survey, as well as additional site visits afterwards with the WRMA monthly monitoring team. In this chapter, the methodologies used for the three assessments are elaborated.

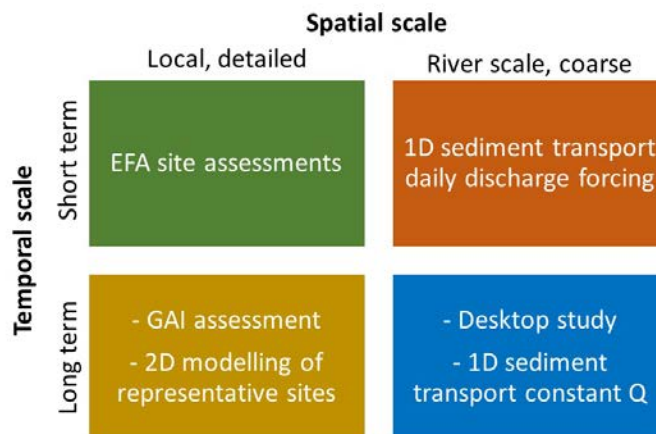


Figure 4.1: Division of morphological assessments that can be made for a river by spatial and temporal scales.

4.1. Desktop study

The desktop study brings data together from behind the computer, before going into the field. It involved tracking the river in Google Earth, extracting the elevation profile from STRM data. This gave the sinuosity ratio for different reaches. The Google Earth imagery also provides insights into the river features along the banks, or instream. Based upon the slope, confinement and probably bedmaterial, the Buffington-Montgomery index is given (Montgomery and Buffington, 1997).



Figure 4.2: All sites where data is available from (Rey et al., 2015, Mtamba et al., 2015, Muthike et al., 2007b, and data acquired for this research.)

4.2. Field survey

The recent EFA surveys were carried out in December 2015 and March 2016 with a team of vegetation, macro invertebrate, fish, water quality, geomorphology and hydrology/hydraulics specialists. In total 8 sites were visited; Nyangores Silibwet, Nyangores Chemomul, Amala Kapkimolwa, Mara Beef, Talek Olare Orok, Sand, Purungat Bridge and Mara Mines, where Mara Mines was only visited in the high-flow survey. The sites are listed on the map in Figure 4.2. Three sites were along the main stream of the Mara. These are Mara Beef, Purungat Bridge and Mara Mines, the latter two at the same location as the EFA 2007-2012. After the EFA survey, additional sites which are monitored by WRMA, were visited with WRMA officers to perform the monthly discharge measurement and to do some additional survey on morphology. Along the main stream of the Mara, Mara Emarti and Mara Kichwa Tempo were added to the list. At these sites, one transect was surveyed with the RiverSurveyor, sediment samples were collected and a mesohabitat mapping was done. This can be seen as a small and quick survey compared with the EFA surveys. Here the method for the elaborated EFA hydraulic and morphological field survey is discussed.

4.2.1. Hydraulic survey

Important for the morphological and hydraulic survey are the transect markers, which set up the transects perpendicular to the flow. Along the line set up by these two markers, the measurements of cross section and velocity are done. These transects are used for the hydraulic modelling, which determines which flows belong to which corresponding water levels.

Discharge and velocity measurements The discharge and velocity are measured by a RiverSurveyor M9, an Acoustic Doppler Profiler together with a hydroboard to carry it and an DGPS mounted on the hydroboard, using the moving boat principle see Figure 4.3 (Sontek, 2010). The boat is pulled from bank to bank gently along a tagline or only with ropes attached to the boat when the discharge is low. The RiverSurveyor Acoustic Doppler Profiler measures the velocity in the vertical every second, while the DGPS mounted to the



Figure 4.3: RiverSurveyor as used in the field (left), as prescribed in the manual of SonTek (Sontek2010) (middle) and the RiverSurveyor M9 ADCP sonde which sends out the sonar signals (right)

hydroboard measures its position. In order to have a good discharge measurement, the flow in the transect should be confined, and have no pools. For velocity measurements this is not required. For each transect, 8-10 runs with the RiverSurveyor are made. The RiverSurveyor software (RiverSurveyorLive) gives the data for velocity, depth and track of the boat for each run. In the processing phase, the runs are selected on the visual interpretation of the straightness of the course of the measurement, the width of the run and the deviation from average discharge.

Cross section measurements The cross section measurements consist of a dry cross section and a wet cross section. The wet cross section is most often measured with the RiverSurveyor, as it was too dangerous to cross the main stream Mara River. Important for the cross section measurements is to include the knick points in the cross section, where the flood benches or terraces start, where water level is located. The measurements went on to well on the terrace.

During the high flow survey, tacheometric surveying was applied using a total station of the brand TopCon and a handheld prism on a staff were used to measure the distances within the dry cross section. From the total station, the distances and angles to points in the cross section where the staff was held were measured. During the low flow survey, a Differential GPS device (DGPS) to measure the positions of the dry cross section. The Post Processed Kinematic method was applied, meaning that the base station and rover data were processed after the measurements. A base station was set up and received positioning data from all available satellites during 4-7 hours. To measure the cross section a second GPS on a Rover was measuring every second its position with the available satellite connections. The hand held staff with the Rover traced all points on the cross section and within the site that needed to be measured. With post processing, the data received by the base station was used for Precise Point Positioning with NRCAN, provided by Natural Resources Canada, Canadian Geodetic Survey. This means that the position of the base is computed in high accuracy positioning, which can then also be translated to the data obtained by the Rover, resulting in a centimetre accuracy of the measured position. There the Rover measured every second, the processing of the data also needed to filter out the unnecessary points measured with the DGPS. Also in a few sites, the GPS did not receive enough satellites for accurate point positioning.

4.2.2. Morphological survey

For the morphological survey, the goal is to map the different habitats and their substrate and hydraulic conditions. This is done with a plan view sketch of the planform of the river, and mapping the habitats on the transect measured in the cross section measurement. In these maps, the key morphologic features and habitats are indicated, as well as bed material, inundation level, and other features.

Sediment samples are taken of the bed, bank and deposited sediments. The bed material, where possible is taken along the transects. The bank material and flood deposits are taken separately from left and right bank, along a distance of approximately 50 m. A Van Veen grab sampler was used to collect bed sediment samples along the transects. During high flows, it was difficult to collect bed samples because of strong current and restrictions by present wildlife. During the low-flow survey, bed sediment samples could be taken more easily as the bed was falling partly dry and flows were much slower. Samples taken during the December survey were analysed in the fish lab of the University of Eldoret. The samples from the field survey in March 2016 were taken to the Netherlands to analyse in the geology lab of the Technical University Delft. Samples were



Figure 4.4: Cross section measurement equipment. From left to right: Total station of TopCon at Mara Kichwa Tempo, Measurement of cross section with the total station at Amala Kapkimolwa, Base station of Trimble R7 set-up and DGPS Rover used to measure the wet cross section at the Amala Kapkimolwa during low flow.

first oven dried for 24 hours, and then sieved with sieves that were available.

For establishing the EFA also the drivers of morphology, connectivity, sediment supply, channel stability and habitat change due to these drivers are rated, as well as bed stability threshold. Finally, the present ecological state and future desired ecological state can then be assessed (a more detailed description is given in Rown-tree, 2013).

In order to extrapolate from site scale to river scale, pictures taken during other surveys are analysed for habitat purposes. These pictures come from Rey et al., 2015, Ndomba, P.M. and Mtamba, 2012, Muthike et al., 2007b and from Anne Liliande (engaged in the MaMaSe project).

4.3. Theoretical analysis

Zooming out from the field measurements to analyse the river at a reach scale, a lot of simplifications and assumptions have to be made. One of them is to analyse the river along the longitudinal axis of the river, for bed load sediment transport. Differences between reaches are recognised for width, discharge, slope and roughness, which are translated to equilibrium parameters of depth and velocity for future and current states. The simplification only takes into account the sediment transport via bed load transport, estimated with Engelund-Hansen. The reaches are characterised as either alluvial, capacity limited reaches, or bedrock reaches supply limited reaches.

The scenarios to be calculated are divided into a reference, EFA floods, EFA maintenance and 95-percentile discharge scenario (which is the amount of water that always should remain in the river determined by legislation Republic of Kenya, 2007). These scenarios will be compared to each other. The reference scenario is based on the parameters found in the field for the representative grain size (as is explained below). The other scenarios are based on the grain size parameters resulting from the reference scenario.

EFA floods, and EFA maintenance scenarios are based on the EFR where the maintenance scenario does not take into account the freshets and the annual and inter-annual floods. The Q_{95} scenario is included since this is the legislative environmental flow estimate when no better recommendation is made.

These simplifications lead to the following implications:

1. The reaches have constant slope, width, and roughness
2. The river is seen as a 1D river where no effects of bends are taken into account
3. The cross section is defined by the width of the river
4. The discharge is simplified to a scheme where water only flows in at Emarti, Talek, Sand, and Mara Mines
5. Tributaries and lateral fluxes into the river only deliver water, there is no sediment flux into the river
6. The roughness is estimated with a general method for river roughness with factors from Cowan, 1956, and verified with the field measurements
7. The sediment transport calculated is the bed material load, calculated by Engelund-Hansen transport formula
8. For the predictions in the future, it is assumed for simplicity that the conditions determined in the

reference scenario (D_{50} , n_m , B) will stay constant

For the calculations of the water levels, sediment transport flux, grain size diameter and flow velocity and depth, the formulas from Section 2.1.2 are applied. In order to use the equations a lot of assumptions have been made, on top of the simplifications above. The calculations are based on an equilibrium state of the river, there rivers always develop towards an equilibrium state between the physical parameters and the sediment transport. This justifies the assumption that the bed load sediment transport in alluvial reaches is the capacity sediment transport, and allows to estimate the sediment fluxes for these circumstances.

The following assumptions are made based on the simplifications and the applicability of the sediment transport formulas, in order to calculate the unknown parameters:

Hydraulic assumptions

1. The monthly average discharge can be simplified to a yearly constant discharge calculated with Equation 2.15. This discharge is representative for calculating the effect of sediment transport processes on the river slope over a year of variate discharges.
2. Uniform flow, sub-critical flow in the reaches.
3. The river is stable for the current observations of slope, width, roughness, D_{50} .
4. The back water curve from Lake Victoria, is not influencing water levels at Mara Mines (downstream boundary of area of interest).
5. The discharge and sediment supply between reach 1 - reach 3a comes only from the upstream boundary, Emarti.

Morphological assumptions

1. Reach 1 and 3 are capacity limited in sediment transport, because there is plenty of fine sediments observed in the cross sections in this reach.
2. Reach 2 is supply limited for sediment transport, because no fine sediments found in the cross section in this reach.
3. Reach 4 has plenty of sediment supply, and thus can be seen as an alluvial part, while the elevation difference is overcome by bedrock outcrops. The bed is thus fixed in this reach.
4. The sediment sizes found in the field give an estimation of the range of the bed sediment load, but is not representative for the bed load, since it was not possible to sample the full bed, only the banks of the river and the sides near the water edge are sampled.
5. In the future, the flux of water will become smaller (EFA), but the flux of bed load sediments (Q_s) coming from upstream, will stay constant.

Boundary conditions Two boundary conditions are needed to solve the hydrodynamic equations, an upstream and a downstream boundary since the flow in the river is subcritical. And to solve the sediment transport also one boundary condition is needed, here the upstream boundary of incoming sediment is chosen.

The discharge data used is based on Hulsman, 2015, for which the model was divided in 7 sub-basins (see Figure 3.1). Using this data set, it is possible to quantify the discharges from tributaries and the lateral inflow. The incoming discharge at Emarti is simplified as the sum of Amala and Nyangores gauging stations, since these stations have a long time series. Additional discharge inflows are chosen to be at the boundary of reaches. The monthly average discharge are used to construct the reference scenario. In Figure 4.5 it can be seen how the discharge data is divided over the length of the river.

The water levels of Lake Victoria would be a perfect downstream boundary, as the river flows into the lake. However, the hydraulics of the wetland between Mara Mines and Lake Victoria, is very dynamic, having bifurcations and interactions with vegetation, and moreover, being under influence of backwater curves. Since the levels of Lake Victoria are not available for this research, the part between Mara Mines and Lake Victoria is not looked into. The distance between Mara Mines and Lake Victoria is about 130 km, and the assumption made here is that this distance is bigger than the distance of a backwater curve from Lake Victoria could reach. The downstream boundary condition however is still the water level at Lake Victoria, which is chosen to be at the same level as the average of normal depth of the river flow at Lake Victoria.

The morphological boundary condition is incoming sediment flux from upstream. It is assumed to be the same as the flux that the river can transport downstream, as the river is assumed to be in equilibrium. Therefore, the incoming sediment flux is calculated analytically with Equation 2.11 in the theoretical analysis, based

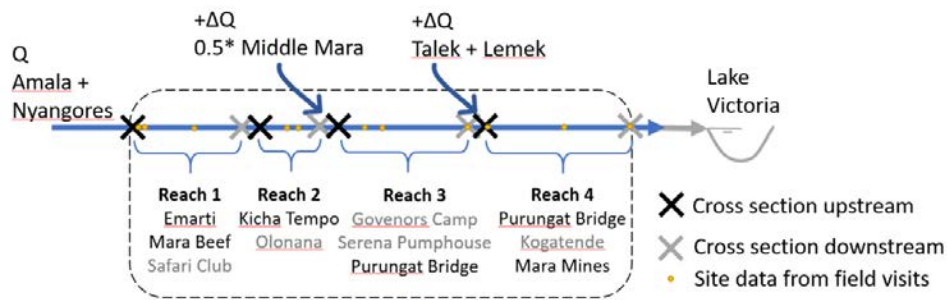


Figure 4.5: Inputs and boundaries of the numerical model. Also per reach the sites are noted of which data in the form of cross section measurements or pictures was available.

on the fact that the sediment flux is equal to the transport capacity in reach 3 (limiting reach for sediment transport). For the reference scenarios, this flux is calculated, and kept constant for other scenarios, as it is expected that the sediment load from upstream will not change. This way of thinking assumes that from the tributaries only water is discharged into the main stem, no bed load sediments.

4.3.1. Analytical calculations

The approach to calculate the sediment transport and changes of slope due to a changing flow regime, which can be calculated assuming the last item in the previous list, are:

1. Representative discharge with the monthly average discharge data from Hulsman with the Equation 2.15.
2. Representative discharge with the EFA discharge with the Equation 2.15.
3. Sediment flux Q_s with the sediment sizes found in the field, with the transport formulas of Engelund Hansen and Meyer-Peter and Müller (Equations 2.11).
4. Sediment size (D_{50}) with the assumption that the sediment transport over the length of the river is constant, and reach 3 is the representative reach for determining the sediment flux in the system with the EH formula.
5. Change in slope with Equation 2.16 and time scale of change with Equation 2.17.

Finally, the short- and long-term responses of the river bed will be assessed for the whole river. Short-term responses are derived from the instantaneous reaction of the water levels. And the long term response is based on the calculation of equilibrium slope from the calculations section. Also an attempt is made to show the possible effects of the incision and the evolution of the bed from that state, as has been illustrated in Section 2.1.2 in Figure 2.4 and Figure 2.3. Key thing with the short term and long term responses, is to start reasoning from the downstream boundary, since there the water level is known, and perturbations of the water level will only travel from downstream to upstream since the flow condition in the river is subcritical.

4.3.2. Numerical model

In the numerical model, the equations for the hydrodynamics and morphodynamics are solved iteratively for each time step. The Sobek-Rivers and Estuaries module is used to calculate the sediment transport with specific monthly discharges, and variations in width of cross section, slope and roughness for each reach. Applying this model gives more insight into the time evolution of the sedimentation and erosion processes. An overview of the schematisation following the schematisation made in the previous section is given in Figure 4.5.

The simplifications for the numerical model are the same as the simplifications (1-7) during the theoretical analysis, since the same equations are used, but only the means of solving them is different. One simplification is different. The discharge for the numerical calculations will become the monthly average discharge forcing the system (simplification 4).

Field parameter In the Engelund-Hansen transport formula, the D_{50} is the representative value for the sediment size to calculate the sediment transport capacity. The outcomes of the previous section (Section 4.3)

are used as a first approximation of the representative grain size sediment under equilibrium transport ($S = \text{constant}$ along the river). Differences in the way of calculation between the theoretical analysis and the numerical model are recognised, and therefore, the D_{50} is adjusted after a first calculation, in order to keep the sediment transport constant for the numerical calculations as well (see first step of the approach). The sediment size is a field parameter, and thus stays constant in time. The sediment size in reach 3 is chosen to be leading, since the alluvial character of this reach is most evident. The representative grain sizes for the other reaches are adjusted on this assumption. The representative sediment size is based on the flood deposits found in the reach, which is sand with a D_{50} of 0.4mm.

Initial conditions For the numerical model, next to the boundary conditions defined in Section 4.3, initial parameters are needed in order to have only the velocity as an unknown at the initiation of the model ($t=0$). The initial conditions for the hydrodynamic calculations are water level throughout the whole length of the river, and discharge in every reach. These values are determined by calculating the normal depth for each reach for the discharges at the beginning of the time series (monthly average of January). The model extend is chosen in such a way that errors arising from this initial condition, will not impact the area of interest (see Section 2.1.4).

The initial condition for the morphology is the initial bed level, as is derived from the Digital Elevation Model.

Numerical parameters The time step of the numerical cells constraint by the Courant restriction. The restriction is that the velocity of a sediment particle times the time step (so the distance of the sediment particle travelled) cannot be bigger than the length of one grid cell, otherwise calculation problems occur in the mass balance between grid cells. The distance between grid cells is determined by the processes that need to be taken into account. In the 1-dimensional model only sediment transport processes in the longitudinal direction are analysed, so only these are interesting to observe. Since the numerical model used is a 1-dimensional model, the length of the grid cells is taken to be larger than the width of the river.

Approach for numerical calculations The steps undertaken are the following:

1. **Representative discharge** The model is forced by the representative discharge, and other parameters as calculated during the analytical calculations. Adjustments for D_{50} and Δz_b at the transitions of reaches for a constant sediment transport flux are done, based on the equilibrium assumption that only small bed level changes along the length of the river are permitted.
2. **Reference scenario** With the new model parameters for D_{50} , topography (the slope stays the same), and sediment transport, the model is forced with the monthly average discharge regime of the historical data. Results include the sediment transport of bed material per month and bed level changes over time.
3. **Run $Q_{representative}$** , and the calculated D_{50} , adjust D_{50} for the way Sobek calculates the hydraulics and morphodynamics
 - a) Assess if the river is stable
4. **Run $Q_{monthlyaverage}$** , with the previously estimated D_{50} .
 - a) Assess the reference state of the river, on the stability
 - b) Assess the magnitude and time scale of the bed level response

5

Results

5.1. Desktop study of the morphology of the river

The desktop study gives results on general characteristics of the river which can be seen from Google Earth and GIS analysis and results into with simplifications of the river.

The elevation profile from STRM data is shown in Figure 5.2. Together with the bedrock map from Section 2, in Figure 2.7 it is identified which geological layers are located in the river course. The Siria Escarpment, bounding the basin at the west side, goes hand in hand with a the steep slope of around 45 km (Mara Kichwa Tempo) in Figure 5.2. Downstream of this section, landforms along the river banks become visible on the surface from satellite images (Figure 5.1). Pictures of tourists (found on the world wide web) provide evidence of active meandering processes (see cover page). This part is assumed to be historically an anastomosing river, while now it is a single thread river (Rowntree, 2016).

From Emarti Bridge to Lake Victoria the river can be characterised in 9 reaches. Starting at Emarti bridge to 10 km downstream Safari Club, the reach is quite meandering, finding some scarce features of old channel beds next to the current river bed. This part is incised for about 6-10 m. Coming closer to the Siria Fault, the river gets steeper and more straightened for the next 21 km (from Safari Club to 6 km upstream Mara Kichwa Tempo). The third reach is located very near to the Siria fault, has a large slope, and based on pictures, bed material is defined as bedrock, boulders and cobbles here. Just downstream of Mara Kichwa Tempo (7 km) a highly active channel is seen from the satellite images. Floodplain features can be seen as the river is able to move within the part that is not covered with trees, see Figure 5.1 (right figure). These floodplain features suggest that enough sediment is available, and thus the sediment transport will be capacity limited. Downstream of this highly active channel, the Talek tributary joins the main stem and the sinuosity of the river is lower. This reach is defined as the fifth reach. The sixth reach starts downstream of Mara Purungat, where the slope increases, and a sequence of riffles can be seen from satellite images. Also sandbars and inset flood benches (sediment supply from the Sand tributary) are distinguished. At Mara Mines the river gets its floodplain features again, increasing sinuosity. Sand bars in inner bends of the meanders are distinguished from the satellite images. Just at the start of the swamp, 30 km downstream of Mara Mines, some meander cut offs are found, happening within four years, from 2010-2014 (seen on Google Earth historical images). Also old river plan form are distinguished here. In the swamp it gets difficult to follow the river, since the river diverges and vegetation is dense. In Table 5.1 the division of reaches of the main stream Mara is summarized by its characteristics and features.



Figure 5.1: Satellite images from the highly active channel downstream Mara Kichwa Tempo (Google). Left: Meander cutoffs (15/03/2013). Right: Floodplain features (17/07/2014).

	Reach	Length (km)	Slope (-)	SI (-)	Features	Buffington Classifica- tion	
1	Emarti - Safari Club	22	0.00064	2.55	Weakly confined, meandering, signs of old meanders, incised +-8 m, agriculture	Pool-riffle Regime	-
2	Safari Club - Kichwa Tempo	21	0.00219	1.3	Weakly confined, straight, incision moderately, rangelands	Pool-riffle regime	-
3	Around Kichwa Tempo	13	0.00508	1.67	Fault confined, large bed material, almost no incision	Step-pool	
4	Kichwa Tempo - Talek confluence	32	0.00095	2.06	Weakly confined, meandering, old meandering riverbed, river incised, national reserve	Pool-riffle Regime	-
5	Talek confluence - Purungat	40	0.00121	2.29	Confined, inset and lateral sand bars, incised, national reserve	Pool-riffle Regime	-
6	Purungat - Kogatende	20	0.00331	1.13	Confined valley floodplain, altering riffles - sand bars and inset flood benches (inflow of Sand; much sand), national reserve	Step-pool Pool-riffle	-
7	Kogatende - Mara Mines	64	0.0036	1.89	Inflow of 11 ephemeral tributaries, slope varies a lot, boundary of the reserve after 35 km, agriculture 35 km downstream of Kogatende	Step-pool Pool-riffle	-
8	Mara Mines - Swamp	28	0.00057	1.73	Sandbars at inner bends, floodplain characteristics, agriculture, smaller width	Regime	
9	Swamp - Lake Victoria	102	0.00033	1.88	River splits up, cannot be traced, smaller width of the part that is traced, densely vegetated	Regime	

Table 5.1: Reaches characterised by slope, sinuosity (SI), and Buffington-Montgomery classification (Montgomery and Buffington 1997)

Table 5.2: Representative discharges for different scenarios. Where $Q_{EFA_{2016}}$ is the discharge recommended without taking into account the freshest and yearly floods, and $Q_{EFA_{floods}}$ taking into account the freshest and the yearly and 5-yearly floods.

Reach	$Q_{current}$ (m ³ /s)	$Q_{EFA_{2016}}$ (m ³ /s)	$Q_{EFA_{floods}}$ (m ³ /s)	Q_{95} (m ³ /s)
1	34.4	6.9	12.2	2.1
2	34.4	6.9	12.2	2.1
3	39.9	8.0	20.0	2.8
4	83.1	8.9	31.26	4.7

Table 5.3: Simplified parameters for the Mara River per reach

	Reach	Length (km)	Width (m)	Slope (-)	Manning n (s/m ^{1/3})	Sinuosity (-)
1	Emarti – Old Mara Bridge	43	27	0.00135	0.0416	1.69
2	Around Old Mara Bridge	13	45	0.00508	0.0455	1.67
3	Old Mara Bridge – Border	72	39	0.00094	0.0494	2.23
4	Border – Mara Mines	84	60	0.00331	0.104	1.63

5.1.1. Simplification of the river

Based on the desktop study, and the representative sites of the field survey, the river is simplified into 4 reaches. Each reach has one site which was visited during the field survey. Reach 1 and 3 are alluvial defined reaches, whereas reach 2 is a bedrock reach. Reach 4 is has much alluvial transport, but the elevation difference is constraint by bedrock appearance. The elevation of the bed is thus defined by bedrock, and therefore this reach is defined as a bedrock reach as well. The simplified profile, and the normal profile can be seen in Figure 5.3. The parameters that are chosen to represent the reaches are summarized in Table 5.3.

The discharge records are simplified to representative constant discharges for each reach. This is based on daily modelled discharge by Hulsman (Hulsman 2015). This daily discharge is transformed to monthly averages and representative discharges. Since the discharge records varied a lot per year, the analysis of the representative discharge was done for 1 year, 5 years and all data respectively. The results can be seen in Figure 5.2. For the scenarios, the EFR discharges are also decimated to constant representative discharges. All representative discharges are summarized in Table 5.2.

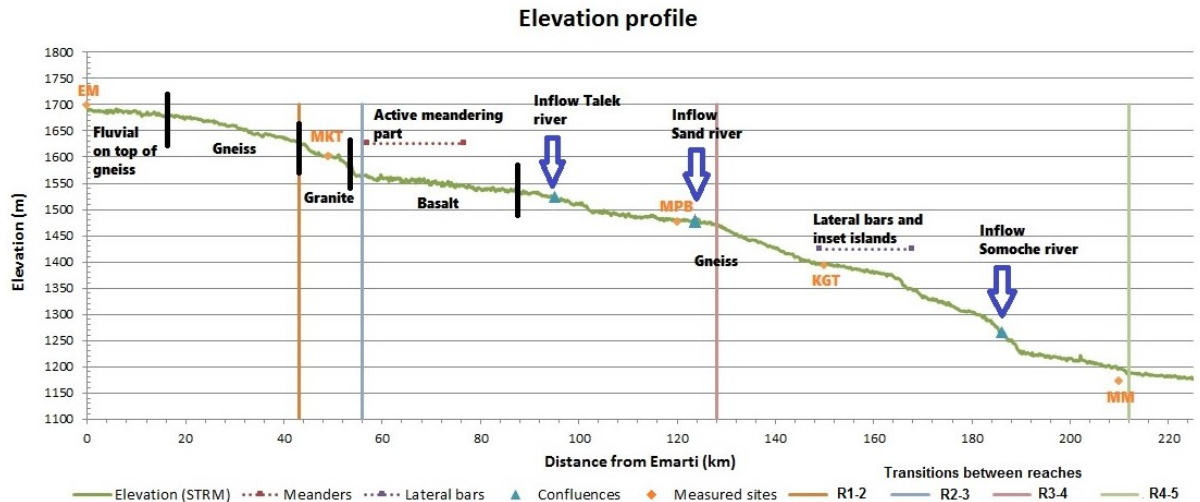
5.2. Field survey

During the local field assessments the discharge, sediment characteristics, and habitats were measured and mapped. Generally, at all sites incision was observed, and at many sites the rate of incision was quite high. Bed rock was found as bed substrate at all sites, governing the hydraulics and bed level of the river. In geomorphological terms, pool-riffle morphology is distinguished at every site, and has been found to be very important and significant for the ecology. The pools and riffles were found at every site. In the following sections, the discharge measurements and the sediment analysis are discussed, followed by a description of the sites with habitat mapping. In the end also Table 5.8 summarizes the characters of the reaches, where for the characterisation also pictures from other surveys were used.

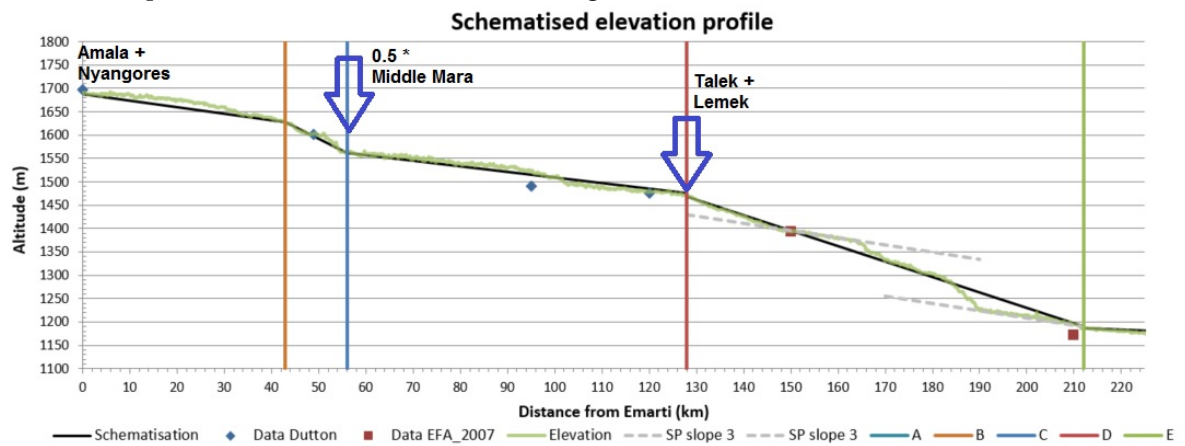
5.2.1. Discharge

The discharges measured at all sites are summarized in Figure 5.4, along with the standard deviation. Since the RiverSurveyor also measures velocity and depth, the Velocity-Depth graphs are made for habitat purposes, given in Figure 5.6.

The discharge measurements with the RiverSurveyor gave a velocity profile as can be seen in Figure 5.5. Discharge measurements where the track of the RiverSurveyor was not recorded well were removed from the data. For the discharge measurement at Mara Mines and Emarti Bridge high flow, the floating method was used as an estimation for the discharge, and thus these measurements do not include a standard deviation in Figure 5.4. In Table 5.4, the Chézy coefficient corresponding with the measurements of discharge and slope for each site are summarized. The highest value of Chézy were found at Mara Mines during high flow and at Purungat Bridge during medium flow (15.88 m³/s) (the Chézy values are respectively 39 and 32 m^{1/2}/s). The lowest values for Chézy were found at Mara Kogatende and Purungat Bridge (11-14 m^{1/2}/s).



(a) Elevation profile extracted from STRM3 data (Google).



(b) Simplified elevation profile, distinguishing 4 main reaches from Emarti bridge, at 0 km to Mara Mines, at 212 km.

Figure 5.2: Elevation profile of the Mara river

Table 5.4: Discharge, slope and flow area results for the sites, converted to the Chézy value for roughness at that site. * = Data from 2007-2012 EFA survey Muthike et al. 2007a; ** = Results from floating method.

Date	Site	Discharge (m ³ /s)	Slope (m/m)	Flow Area (m ²)	Chezy (m ^{1/2} /s)
05-12-2015	Emarti	53.785	0.00124	55.678	21
05-12-2015	Emarti	47.535	0.00124	41.66	20
30-11-2015	Purungat Bridge	96.403	0.00226	72.10	23
01-12-2015	Purungat Bridge	75.017	0.0004	59.21	45
29-02-2016	Purungat Bridge	6.179	0.0004	37.908	11
01-03-2016	Purungat Bridge	5.505	0.0025	11.35	14
03-2007	Purungat Bridge*	7.471	0.00155	20.46	11
07-2007	Purungat Bridge*	15.88	0.0003278	28.60	32
03-2007	Safari Club*	6.842	0.0018036	10.88	24
07-2007	Safari Club*	16.896	0.0017034	17.77	29
02-2012	Kogatende*	2.56	0.0031	6.485	11
05-2012	Kogatende*	117.98	0.000667	115.108	12
02-2012	Mara Mines*	2.5	0.001558	11.652	18
05-2012	Mara Mines*	529.32	0.000623	248.5	39
28-11-2015	Mara Mines**	676.8	0.000972	289.25	36

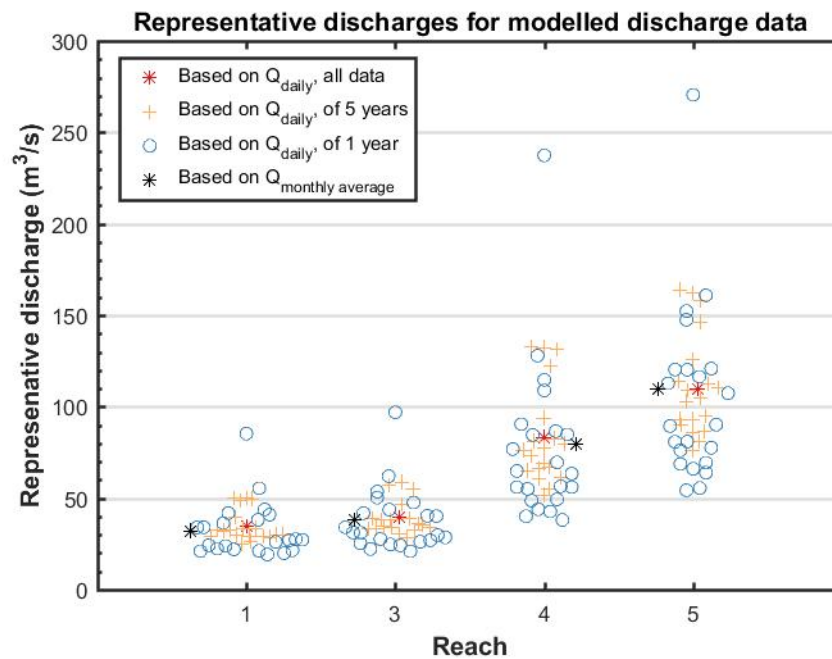


Figure 5.3: Representative yearly discharges for records of Hulsman 2015. Representative discharge is calculated by Equation 2.15 for monthly average discharge and daily discharge.

5.2.2. Sediment analysis

Most bed material appeared to be coarser than gravel in the main stem, and much bedrock is found in general, sometimes covered with gravel or sand. Gravel and sand pockets were found exposed along the river banks. In Table 5.6 an overview of the sites, with the type and size of the sediment can be found. The boulders found at Mara Kichwa Tempo are expected to originate from the bedrock, as around Emarti and Mara Beef such big boulders are not found.

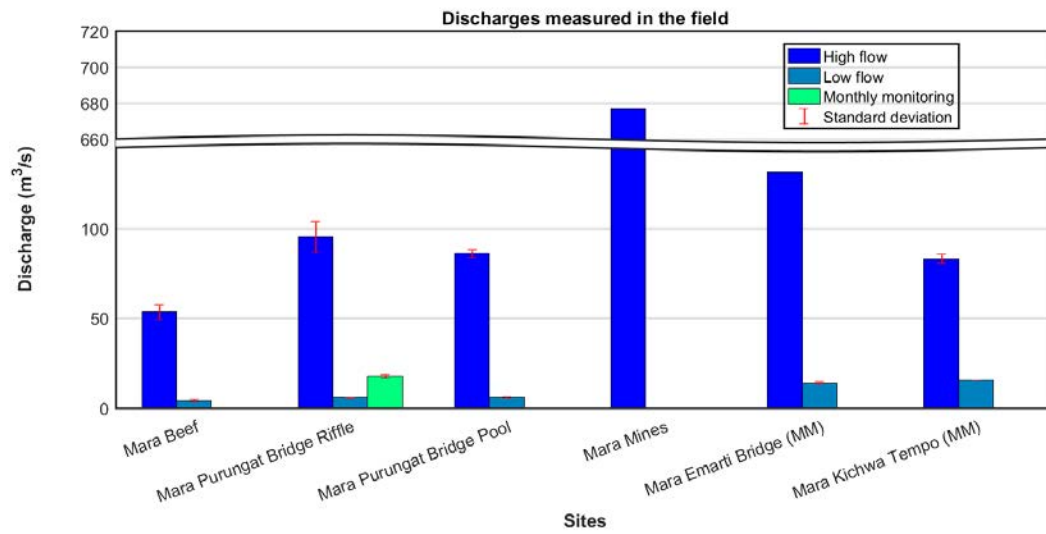


Figure 5.4: Discharges measured during the field survey. Mara Emarti Bridge and Mara Kichwa Tempo were visited during monthly monitoring (MM) with WRMA.

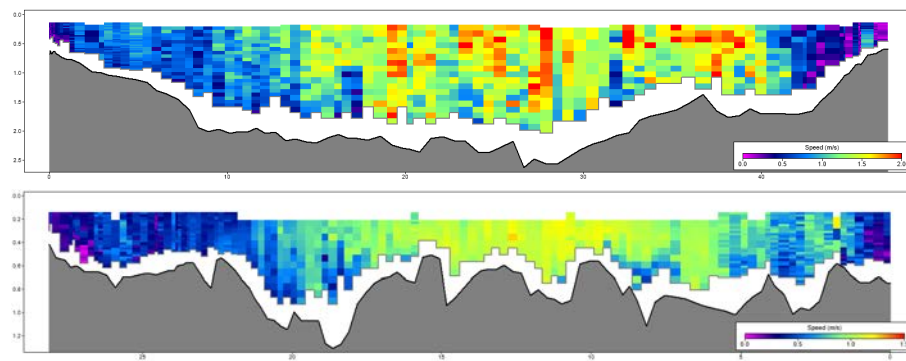


Figure 5.5: Upper: Velocity profile on 15th of December 2015. Measured parameters are: Discharge $81.9 \text{ m}^3/\text{s}$, maximum velocity 2.14 m/s , width 46.5 m and maximum depth 2.5 m . Lower: Velocity profile on 9th of January 2016. Measured parameters are: Discharge $15.6 \text{ m}^3/\text{s}$, maximum velocity 1.25 m/s , width 28.6 m and maximum depth 1.2 m .

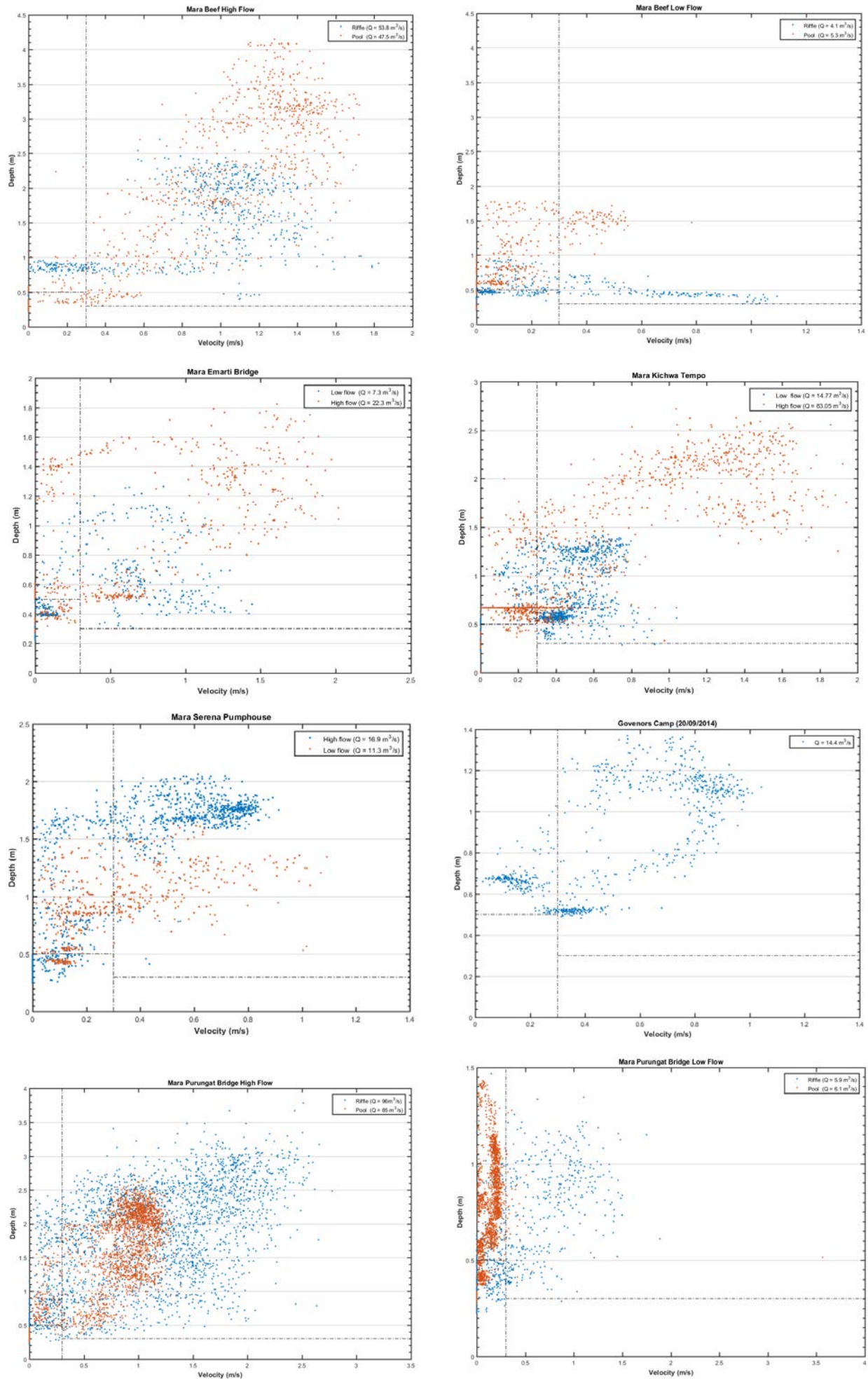


Figure 5.6: Velocity depth graphs for all measured sites, including Serena Pumphouse and Govenors Camp in the meandering part of the river (measured by Rey et al. 2015).

Table 5.5: Sediment classification of bed and bank material for all sites along the main stream Mara. For the grainsize distributions and specific sizes, see Appendix C. * = Based on data and pictures from 2007-2012 EFA survey Muthike et al. 2007a, Mwanukuzi 2011, ** = Assumption based on pictures from Rey et al. 2015.

Main stream Mara		
<i>Site</i>	<i>Bed material</i>	<i>Flood bench material</i>
Mara Beef riffle	Bedrock, boulder, cobble	Vegetated, steep bank
Mara Beef pool	Medium sand	Vegetated, fine sand
Emarti	Bedrock, boulder/cobble	Bedrock, consolidated soil
Safari Club*	Cobble/Boulder	Coarse sand, small cobble
Kichwa Tempo	Bedrock and boulder	Medium sand
Serena Pumphouse**	<i>Sand</i>	<i>Vegetated, sand</i>
Govenors Camp**	<i>Sand</i>	<i>Sand, grass</i>
Purungat Bridge	Small cobble over bedrock	Coarse gravel and sand
Kogatende*	Sand, bedrock	Sand, grass
Mara Mines	Medium, coarse sand	Bedrock, sand
Tributaries		
<i>Site</i>	<i>Bed material</i>	<i>Flood bench material</i>
Talek riffle	Bedrock	Coarse gravel, sand
Talek pool	Coarse gravel, medium sand	Grass, fine sand
Sand	Coarse sand - gravel	Grass, fine sand
Nyangores	Large cobble	Very fine gravel in pockets
Amala	Large cobble	Very coarse sand in pockets

Table 5.6: Sediment samples from all sites along the main stream Mara, for the grainsize distributions, see Appendix C. * = Data from 2007-2012 EFA survey Muthike et al. 2007a.

Site	Location	Sediment classification	Sediment size <i>D₅₀ - D₉₀ (mm)</i>
<i>Main stream Mara</i>			
Mara Beef	Slow flowing eddy	Medium sand	0.4-0.9
Mara Beef	Flood bench	Fine sand	0.17-0.4
Mara Beef	Riffle bed	Very coarse gravel/Pebbles	34-43
Mara Beef	Left bank	Coarse sand	1.12->2
Mara Beef	Right bank	Fine sand	0.12-0.18
Emarti	Left bank	Medium - coarse sand	0.3-3.0
Emarti	Right bank	Very coarse sand - gravel	1.5-20
Safari Club*	Bed material	Cobble/Boulder	500- -
Safari Club*	Sediment pockets	Coarse sand - Small cobble	0.5-128
Kichwa Tempo	Deposits along river bank	Medium sand	0.23-1
Kichwa Tempo	Bed material	Boulders and bedrock	500- -
Purungat Bridge	Bed material	Small cobble over bedrock	89-120
Purungat Bridge	Deposits in active channel	Coarse gravel	30-38
Purungat Bridge	Flood deposits	Coarse sand	1.3-2.3
Purungat Bridge	Flood deposits	Fine sand	0.22-0.6
Mara Mines	Grab sample right bank	Medium - coarse sand	0.4-0.9
<i>Tributaries</i>			
Talek	Right bank flood deposits	Fine sand - Coarse gravel	48-54
Talek	Bed material	Coarse gravel - medium sand	
Sand	Bed material	Coarse sand - fine cobble	
Nyangores	Bed material	Large cobble	132-198
Nyangores	Sediment pockets	Very fine gravel	3.3-20
Amala	Bed material	Large cobble	160-180
Amala	Sediment pockets	1.6->2	Very coarse sand

5.2.3. Habitat mapping

Along most sites, it can be seen that bedrock provides riffle flow and therefore more turbulence, which is good for the habitat variability and substrate diversity. The incision constrains this variability by confining the flow in lateral direction to the main channel, as the flood benches are eroded in confined parts.

The difference between the habitat coverage during high-flow and low-flow surveys is very large, and provides much insight into the different characteristics. During the high-flow survey most of the cross section of the river was under water, which became clear only during the low-flow survey. During the latter survey, more diversity in substrate and hydraulic habitat and vegetation was visible, while during the high-flow survey these areas were inundated, providing different habitat for ecology. During the low-flow assessment (discharges close to 95 percentile discharges, Q_{95} , the legislative environmental flow recommendation), coverages of flood benches, and marginal zones is lacking, therefore less habitat coverage and diversity is present, especially in the pool sections. In the riffle sections turbulent and fast flow is still present, but the area of different habitat coverage for these low discharges is very small. In Figure 5.7 to Figure 5.10 the plan view and cross section is provided. In Table 5.7 the available habitat for every site is shown. Also pictures from these and other surveys during different hydraulic states of the river are shown in Figure 5.13 and Figure 5.12. The main features categorised per reach are summarized in Table 5.8. A more detailed discussion per site can be found in Appendix C.

5.2.4. Velocity-Depth habitat

The discharge data from the RiverSurveyor measurements, provide for each time the ADCP receives an echo, the depth and the velocity. With this data, velocity-depth relationships are plotted in Figure 5.6. For a reliable discharge measurement the transect should be confined and without surface waves, and measurements were done at confining parts of the river. While for habitat surveying the transect should be representable for the hydraulic habitat found at that site. Also the equipment itself has its influence on the relationship between velocity and depth. The RiverSurveyor measures the depth and velocity every second, while the procedure of measuring considers half a minute of stationary measurement at both banks. This explains the trend of the horizontal line in the figures for Mara Kichwa Tempo, Mara Emarti Bridge, and Govenors Camp. Also, it can be seen that few percentage of habitat is shallow, this is because the RiverSurveyor is only measuring velocity from depths larger than 20 cm.

Bearing these facts in mind, the following observations are clear for the velocity-depth graphs. Distinct pool and riffle behaviour can be seen at Mara Purungat Bridge. During high-flow the velocity and depth for the pool section are much more confined than the measurements for the riffle section. For the low-flow measurement, the velocities of the pool section varied within a small band between 0-0.3 m/s, which is classified as mostly slow-deep flow. For the riffle section the velocities were still spread out and ranged from 0 to 2 m/s during low-flow conditions. Compared to high-flow, this is almost the same spread as for the riffle section (0-2.5 m/s).

At Mara Beef, the differences between the riffle and pool flow are explained by the fact that the depths in the pool section were larger than in the riffle section. The velocity range for riffle and pool are quite alike during high-flow circumstances, ranging from 0 to 1.8 m/s. For low-flow, the pool section depths are bigger and velocities lower, while at the riffle section the depth is lower and less variable while the velocities are more spread out than for pool flow. For these low-flow circumstances it can thus be seen that the coverage of deep-fast hydraulic habitat is very small along the measured transects.

At Emarti Bridge and Kichwa Tempo more or less the same pattern is recognised, namely that for high-flow the velocities and depths are more spread out than at low-flows. The measurements at these sites were only made for 1 transect. Mara Kichwa Tempo can be seen as a riffle flow, while Mara Emarti bridge can be classified as a plane bed flow.

Velocity-depth plots for Mara Serena Pumphouse and Govenors Camp are made using data from Rey et al. 2015. The aim was to see if any interesting features would be visible in the data. It can be seen that for Serena Pumphouse the difference between high- and low-flow is that the depth is becoming smaller for low-flow, which can mean that the river cross section has steep banks. From the pictures taken at this site, this assumption is supported.

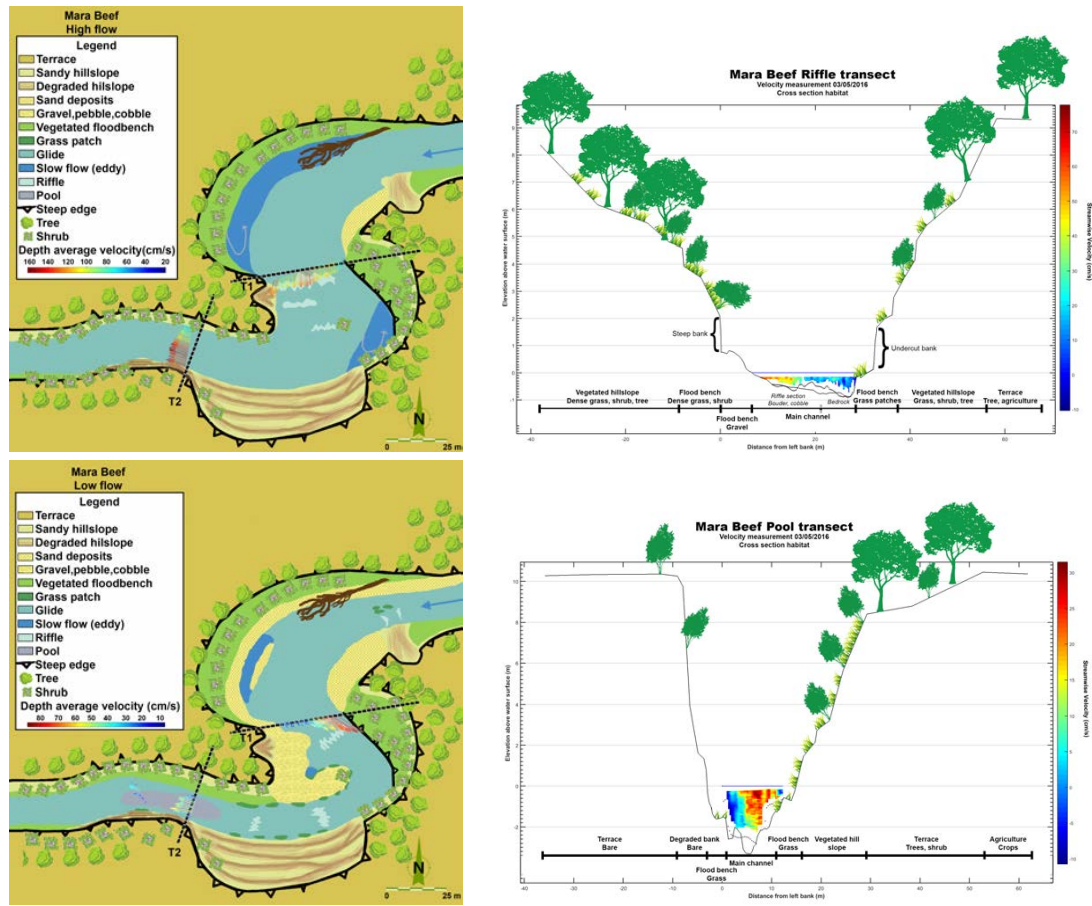


Figure 5.7: Habitat maps plan view and cross section for Mara Beef. $Q_{high} = 54 \text{ m}^3/\text{s}$, $Q_{low} = 4.7 \text{ m}^3/\text{s}$. Large differences in terms of flow direction, hydraulic habitat and flood benches between high-flow and low-flow planviews can be identified.

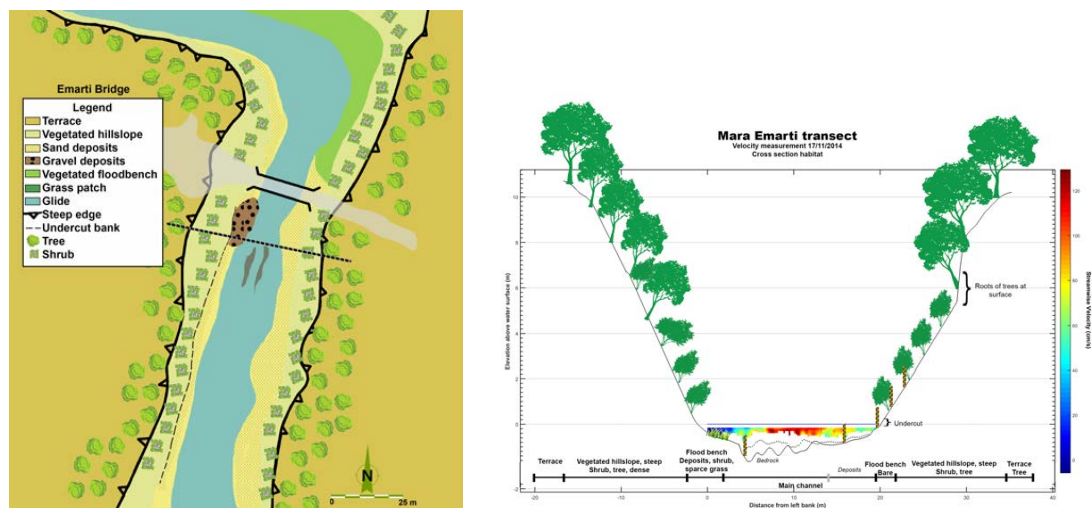


Figure 5.8: Habitat maps plan view and cross section of Mara Emarti Bridge. For the plan view; discharge is very low, and habitats are estimated from pictures of Anne Lilande (see Figure 5.13).

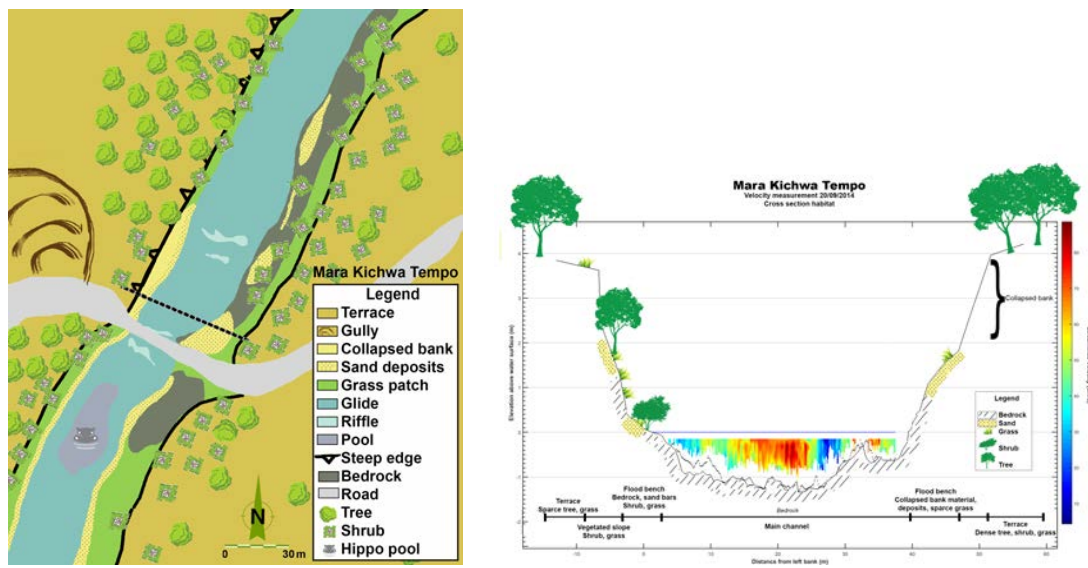


Figure 5.9: Habitat maps plan view and cross section for Mara Kichwa Tempo. $Q = 15.1 \text{ m}^3/\text{s}$. The right bank is quite steep, whereas the left bank is less steep, consisting of sand pockets alternating with bedrock.

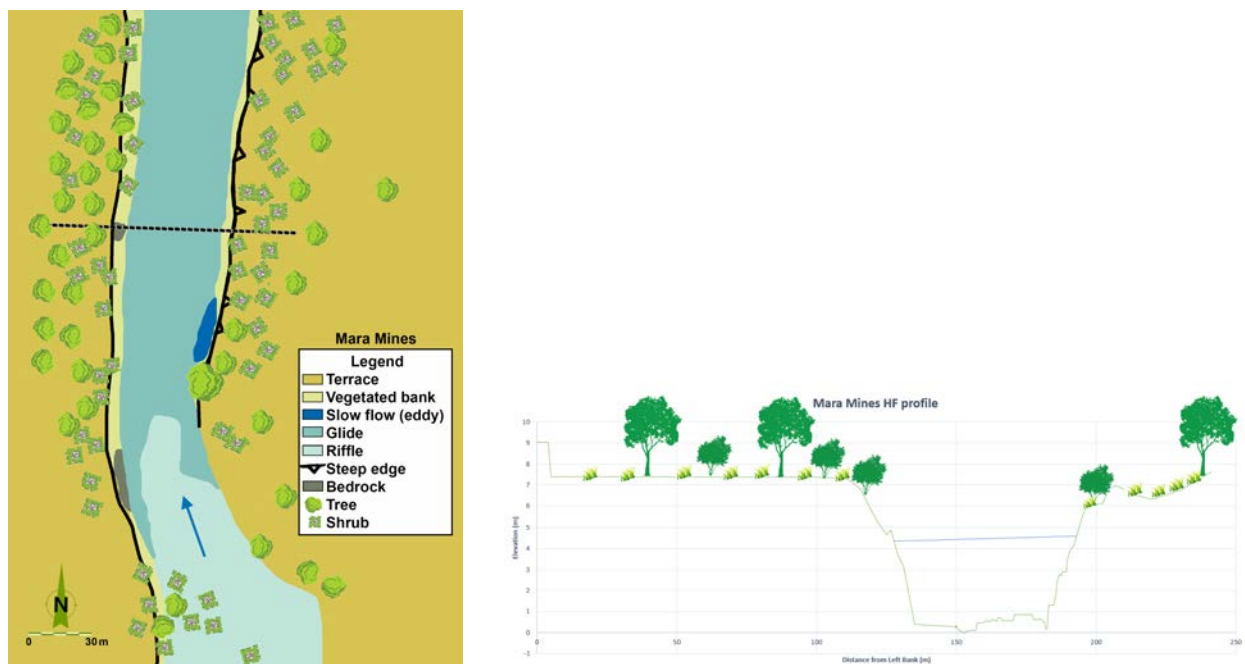


Figure 5.10: Habitat maps plan view and cross section for Mara Mines. $Q = \pm 670 \text{ m}^3/\text{s}$. Distinct alluvial and bedrock section is visible (bedrock upstream, in the riffle section and alluvial along the transect and further downstream). A big tree provided shelter and a backwater area on the right bank. The riffle section was wider and not incised, and contained instream shrubs, recruited on a point bar (this could be seen from the satellite image on Google Earth).

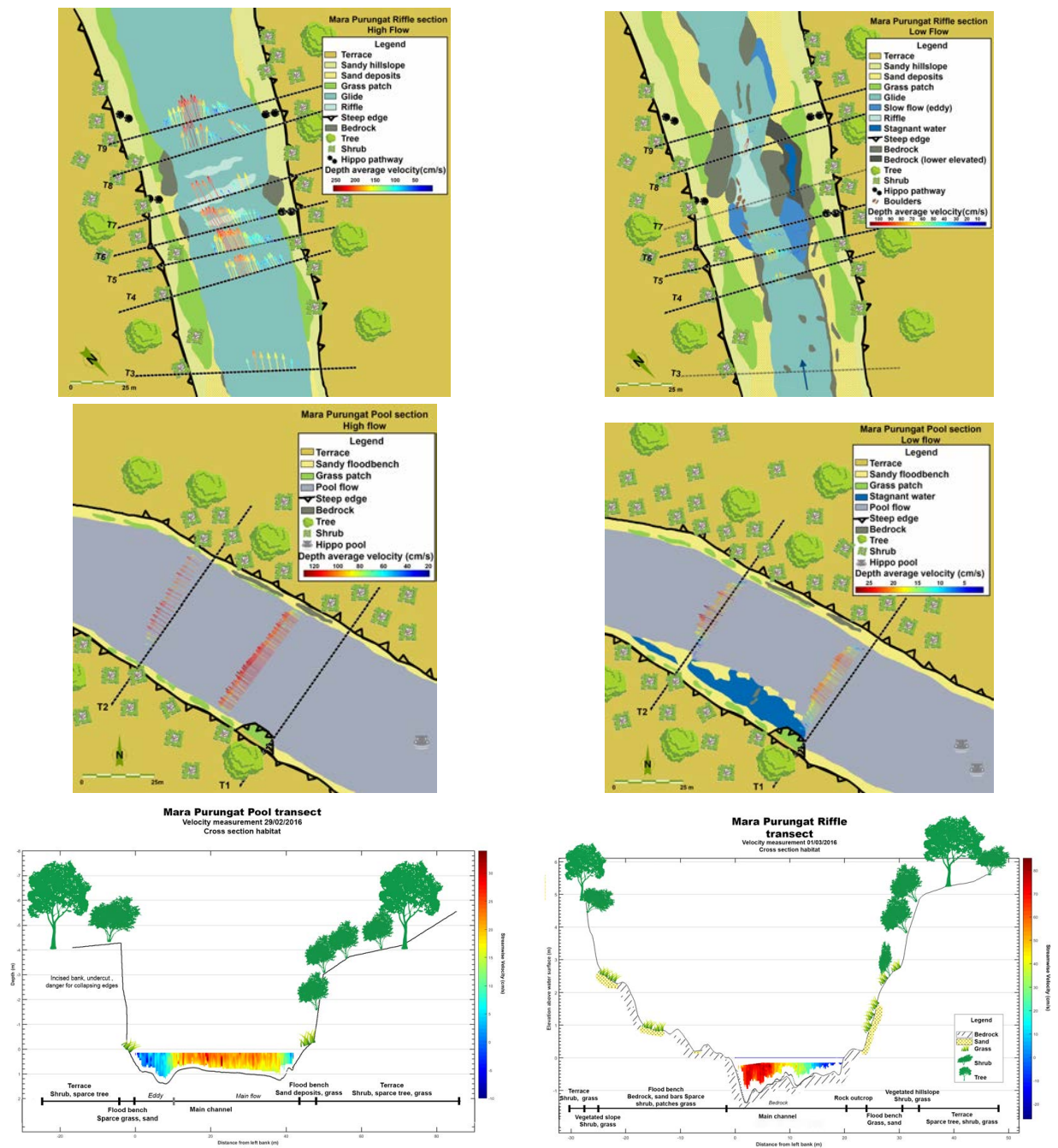


Figure 5.11: Habitat maps plan view and cross section for Mara Purungat Bridge, pool and riffle section for high- and low-flows. $Q_{highflow,riffle} = 96 \text{ m}^3/\text{s}$, $Q_{highflow,pool} = 75 \text{ m}^3/\text{s}$; $Q_{lowflow,riffle} = 5.5 \text{ m}^3/\text{s}$, $Q_{lowflow,pool} = 6.1 \text{ m}^3/\text{s}$. The pool section has much less hydraulic and geomorphologic habitat diversity because of the incision. The riffle section has much more diversity.

Table 5.7: Overview of instream, flood zone and hydraulic habitat for all sites along the mainstream Mara river. ? meaning that is was suspected that these habitats were present, but these were not accessible during the field surveys.

Habitat		Sites										
		Mara Beef		Mara Emarti		Mara Kichwa Tempo		Mara Purungat Pool		Mara Purungat Riffle		Mara Mines
Instream	Fine sand	?		-		-		-		-		?
	Coarse sand	✓		?		-		-		✓		✓
	Consolidated soil	✓		?		-		✓		-		-
	Cobble	✓				-		-		✓		
	Boulder	✓				✓		-		✓		
	C/B over bedrock	✓		✓		✓		-		✓		-
	Inset sand bar	✓(LF)				-		✓*		-		-
	Inset shrub	✓(HF)				-		-		=		✓
	Bedrock	✓		✓		✓		-		✓		✓
Hydraulic		HF	LF	HF	LF	HF	LF	HF	LF	HF	LF	HF
	Glide	✓	✓	✓	?	✓	?	✓	✓	✓	✓	✓
	Riffle	✓	✓	-	?	✓	?			✓	✓	✓
	Backwater	✓			?	-	?			✓(small)	-	✓
	Pool	-	✓		?	✓	?		✓		✓	-
Flood zone (marginal zone?)	Flood bench	✓		✓(very small)		✓(LB)		✓(RB)		✓		only LB
	Sand	✓				✓(LB)		✓(RB)		✓		✓
	Grass	✓		-		-		✓		✓		✓
	Shrub	✓		✓(sparce)		✓		-		✓(sparce)		✓(LB)
	Bank slope	>45 deg		>45 deg		>45deg(RB) <45deg(LB)		>45deg		+ - 45deg		45deg LB, >45deg RB
	Undercut bank	✓(small)		✓		-		✓(LB)		-		✓(small)
	Incised	✓		✓		-		✓		✓		✓



(a) River bed at Mara Mines during low flow (picture from GLOWS-FIU, 2012)



(b) River bed at Mara Mines, riffle, during high flow



(c) Serena Pumphouse during low flow (meandering incised part) picture from Ingrid de Loof



(d) Govenors Camp during low flow (meandering part) picture from Ingrid de Loof



(e) Tributary just upstream Purungat Bridge, incision clearly visible



(f) Tributary just upstream Purungat Bridge, shows diversity of substrate and cross section.

Figure 5.12: Pictures of characteristic morphological features of the Mara river.

Table 5.8: Field work habitat and information of pictures transformed to general reach habitat. LB = left hand bank, RB = right hand bank.

Reach	Character	Site	Habitat
1	Incised to bedrock (8-10 m)	Mara Beef	Alluvial up- and downstream ; -Overhanging vegetation (fish) -Riffle; boulders -Sand bar eddy, woody debris
		Mara Emarti Bridge	-Vegetated bench in upper bend up bridge - RB undercut bench -LB shelf with sparce shrub -Steep vegetated (shrub) banks >45
		Safari Club	-Bedrock/boulders -Riffle , inset grass -RB: overhanging vegetation, steep -LB: Bedrock with grass, wood debris
2	Steep, bedrock	Mara Kichwa Tempo	-Boulder at Riffle - LB bankslope <45, sand bars, shrub -Hippo pool downstream bridge -Wood debris
		Olonana	-Boulder -Small riffle, gentle flow, glide/run -Wood debris -Bank slope «45 -Banks densely vegetated grass, shrub, tree -No incision, no confinement, very wide
3	Alluvial, incised, meander cut-offs more recent. Consolidated rock,	Oxbow	-Small riffle, back water, wood debris -Steep banks; >45; 90 roots of tree through bank -Grass flood benches, sand bench -Over hanging vegetation from terrace (shadow)
		Serena Pumphouse	- Pool with wood debris, plane bed -RB: <45, grass -LB: dense shrub (inner bend) >45
		Govenors Camp	-Steep banks >45 - 90 -Alluvial, few boulders (4) -Bare banks, under cut, steep with grass -RB grass, slope +- 45 (elephant watering point -Trees on terrace -Gentle flow, back water -Overhanging shrub from terrace to bankslope
		Mara Purungat Bridge (riffle)	-Banks <45 -bedrock, outcrops of bedrock, boulders -Sand benches with grass and sparce shrub -Backwater, bedrock pools
4	Alternating steep/less steep, alluvial/bedrock parts	Mara Purungat Bridge (pool)	-LB +- 90, undercut, collapsing -RB >45, bedrock and sand, grass, overhanging shrub -Low flow: stagnant water/back water at LB -Hippo pools and paths
		Mara Kogatende ranger post	-Alluvial, +- 5% bedrock -Riffle, plane bed -Steep banks, incised; grass on steep bank -Flood benches grass, sand bar -RB signs of collapse, undercut -Inset and lateral sandbar
		Mara Mines	-Alluvial; -RB bank slope >45; collapsing, grass, shrub -LB bank slope 45 bedrock outcrop, sand, densely vegetated shrub, tree, grass -Back water eddy during high-flow -Riffle; point bar, shrub vegetated -Riffles, shrub



(a) River bed at Mara Beef; incised channel



(b) River bed at Mara Emarti



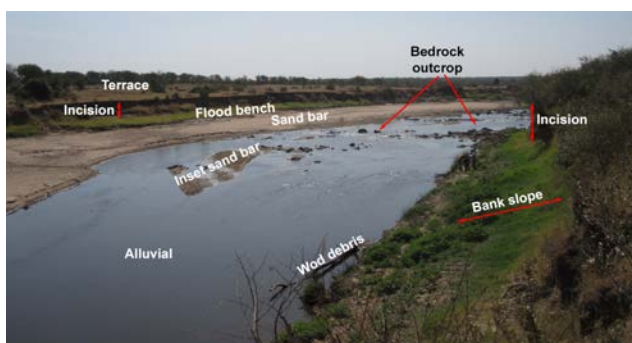
(c) River bed at Mara Kichwa Tempo



(d) River bed at Mara Kichwa Tempo, looking at left bank



(e) Mara Purungat Pool section



(f) Kogatende (picture from GLOWS-FIU, 2012)



(g) River bed at Mara Purungat Bridge, from bridge looking downstream

Figure 5.13: Pictures of characteristic morphological features of the Mara river.

5.3. Theoretical analysis

The long-term and river-scale assessment was done based on sediment transport principles from river engineering. Calculations of annual sediment transport, characteristic time scale of adaptation and changes in equilibrium slopes are made for different scenarios. The results are discussed in the following sections, for the reference scenario and for EFA scenarios.

5.3.1. Reference scenario

The sediment transport capacity based on parameters from the field shows that the lowest capacity occurs at reach 3, which is the alluvial, meandering reach (see Figure 5.14 and Figure 5.15). Also visible from these graphs is that for all discharges but Q_{95} , the Meyer-Peter and Müller transport formula results in larger sediment transport capacity than the transport capacity calculated with Engelund-Hansen. This is expected as MPM includes the threshold of the critical shear stress that has to be overcome to transport the sediment.

Based on the sediment transport calculated with the Engelund-Hansen formula, the river discharges annually 470.000 m³ sediment into Lake Victoria, for the reference scenario. This is based on the sediment transport capacity of reach 3 (meandering reach), which is found leading for the sediment transport calculations. Translated to mass, the volumetric 470.000 m³ sediments is equivalent to 1.2 million tons of sediments.

The numerical calculations for the reference scenario show a constant bed level within the reach for the case with the constant, representative discharge, see Figure 5.17. The bed level increase within one reach is equal along the length of that reach. Between reaches, bed level steps occur. Reach 4 is not yet in equilibrium after 500 years.

The hydraulic results of the numerical model for the monthly averaged discharge scenario are compared with field data for the velocities. This provides a check of the model outcomes for the hydraulic situation, see Table 5.9. For Reach 2, where the results of Mara Kichwa Tempo are used, the model overestimates the velocity. In general, the order of magnitude of the velocity satisfies the field measurements.

The morphological results show aggradation for reach 1 and 2, decreasing the slope. Reach 3 is increasing in slope, experiencing aggradation in the upstream part, and erosion in the downstream part. Reach 4 is again experiencing an erosion wave. The increase of slope over reach 3 is 7.5m over 72km.

The corresponding sediment transport fluxes are shown in Figure 5.19. These graphs show that reach 3 has a low transport capacity in the first year. A low transport capacity consequently means that sediment is deposited at the start of the reach, as the capacity is not high enough to transport it downstream. This sedimentation causes an increase in slope over the reach. Therefore, over time, the sediment transport capacity over reach 3 increases, while, at the same time the slope is increasing as well. The months March-June have the highest sediment transport.

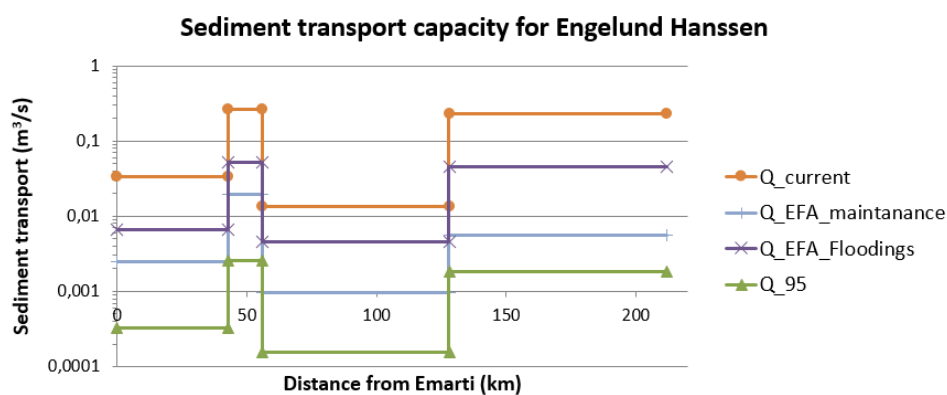


Figure 5.14: Difference in sediment transport for each reach, based on the representative discharge for Engelund-Hansen transport formula.

Table 5.9: Hydraulic results from Sobek model compared with field measurements * = data obtained from literature (Ndomba, P.M. and Mtamba, 2012 and Muthike et al., 2007b) ** = surface velocity; measured by floats (*0.7 = 2.0 m/s). Only high discharges are displayed, there the low discharges are not modelled because of the monthly average input of discharge.

	Site	$Q_{measured}$ (m^3/s)	$u_{measured}$ (m/s)	Q_{model} (m^3/s)	u_{model} (m/s)
R1	Mara Beef December	47.5	1.14	47.21	1.09-1.12
R1	Emarti Bridge October	22	0.927	22.3	0.82-0.85
R1	Safari Club* July	17	0.865	17	0.74-0.76
R2	Kichwa Tempo September	15	0.460	15	0.82-0.835
R2	Kichwa Tempo December	82	1.04	50	1.25-1.35
R3	Serena Pumphouse September	13	0.419	15.5	0.51-0.54
R3	Purungat Bridge December	75	1.267	60	0.85- 0.87
R4	Kogatende* May	118	1.02	118	0.82-0.89

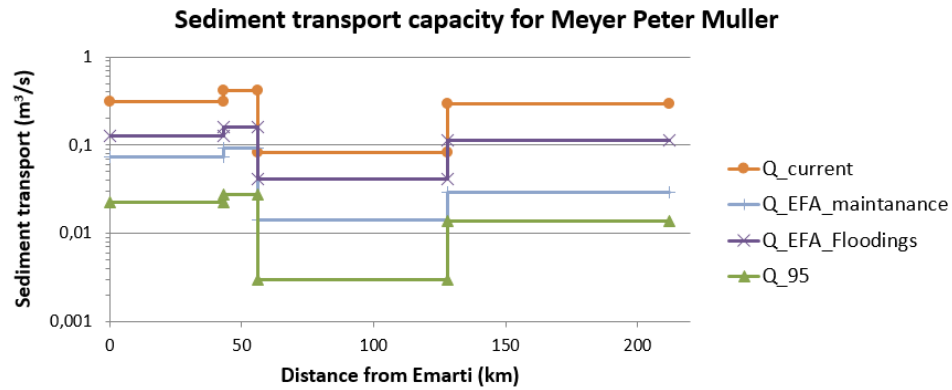


Figure 5.15: Difference in sediment transport for each reach, based on the representative discharge for Meyer-Peter-Muller transport formula.

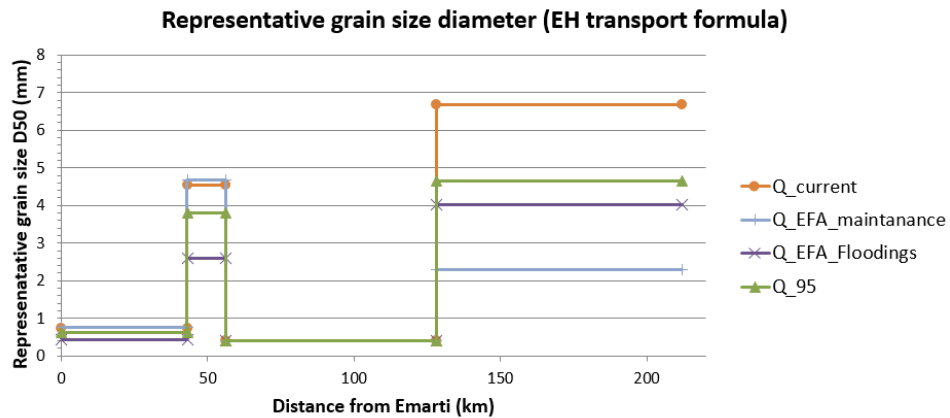


Figure 5.16: Representative grain size diameter D_{50} when the sediment transport is constant over the length of the river.

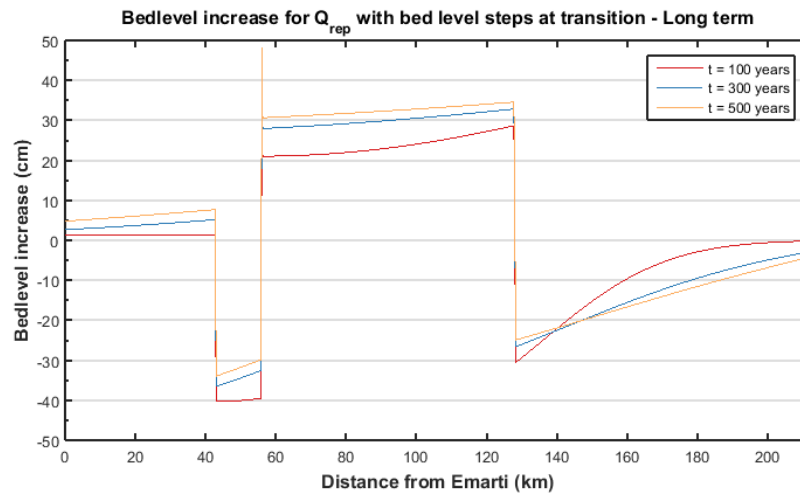


Figure 5.17: Long term bed level increase for Q_{rep} , after 100, 300 and 500 years. The topography includes bed level steps at the transition of reaches.

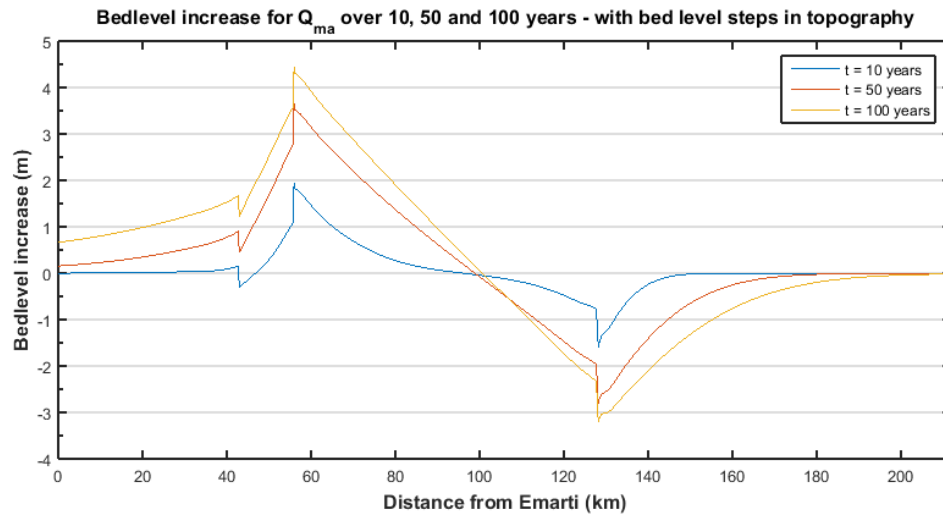


Figure 5.18: Long term bed level increase for Q_{MA} , after 10, 50 and 100 years. The topography includes bed level steps at the transition of reaches.

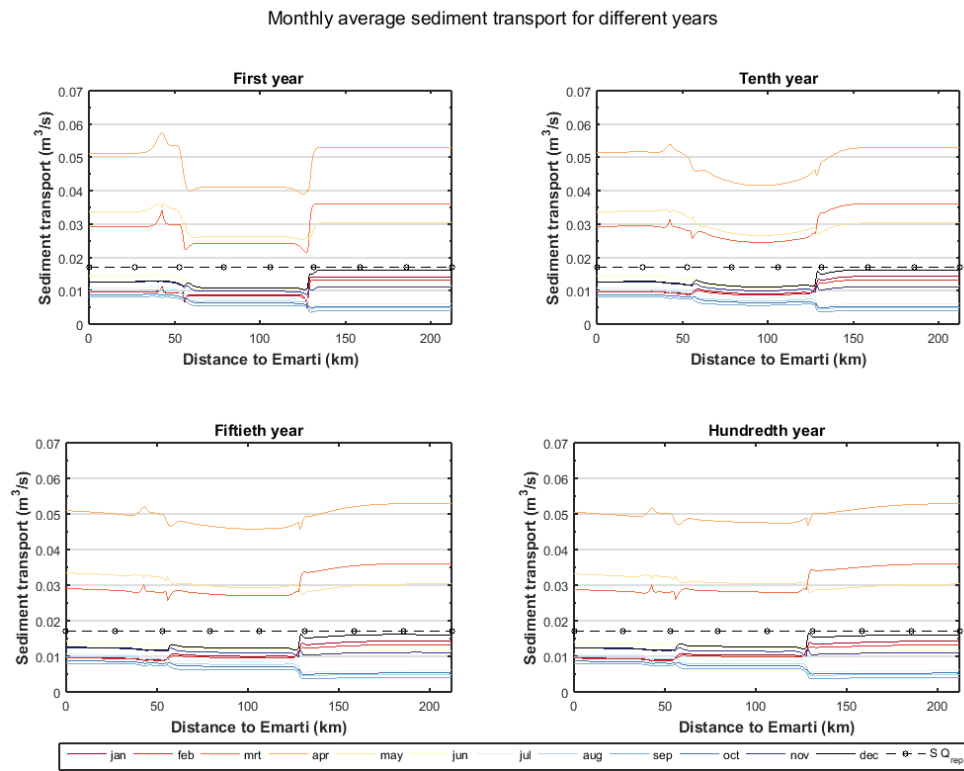


Figure 5.19: Average sediment transport per month for 4 years in the time series. March, April and May having the highest amount of average sediment transport.

Table 5.10: Changes of slope, velocity and depth compared with the current parameters for new equilibrium state scenarios $Q_{EFA, floodings}$, $Q_{EFA, maintenance}$ and Q_{95} . ref = reference scenario; ∞ = new equilibrium for EFA scenario.

	$Q_{EFA, floodings}$				$Q_{EFA, maintenance}$				Q_{95}			
	ΔQ (m ³ /s)	$\frac{i_{\infty}}{i_{ref}}$	$\frac{u_{ref}}{u_{\infty}}$	$\frac{h_{ref}}{h_{\infty}}$	ΔQ (m ³ /s)	$\frac{i_{\infty}}{i_{ref}}$	$\frac{u_{ref}}{u_{\infty}}$	$\frac{h_{ref}}{h_{\infty}}$	ΔQ (m ³ /s)	$\frac{i_{\infty}}{i_{ref}}$	$\frac{u_{ref}}{u_{\infty}}$	$\frac{h_{ref}}{h_{\infty}}$
1	22	2.8	1.5	1.9	28	5	1.9	2.6	32	16	3.1	5.4
2	22	2.8	1.3	3.6	28	5	1.9	2.6	32	16	2.7	10.3
3	20	2.0	1.8	1.4	32	5	1.9	2.6	37	15	3.9	4.6
4	52	2.7	1.9	1.3	74	9	2.4	3.8	78	18	4.1	4.0

5.3.2. Response to changes in flow regime

Generally, alluvial rivers will steepen when discharges decline. The sediments coming in from upstream cannot be transported by the lower discharges, and thus settle down. This sedimentation proceeds until the slope has increased to the circumstances that the incoming sediments can be transported again. In the resulting situation there is morphological equilibrium again. Factors of increase for the slope range from 2-5 for the EFA scenarios. The results for Q_{95} are unrealistic high. The equilibrium slopes, depths and velocities are calculated for the new equilibrium situation, and summarized in Table 5.10.

The changes in slope are translated to bed level increase at the beginning of the reach. Since the differences in slope are large, also the increase in bed level elevation is. It is recognised that the changes in slope can also be reached by changes in sinuosity. The results for this are shown in Table 5.11.

This can be explained by the big difference in Q , and the big length of the reaches. Especially for reach 4 the bed level aggradation is very large. This is because the reach is simplified as a very steep alluvial reach, and the length of the reach is also long (72 km). In reality reach 4 is expected to have alternating bedrock-alluvial parts. This aspect with respect to the bed aggradation is discussed in Chapter 6.

In Figure 5.20 the resulting bed level changes are illustrated, as well as the initial response mechanism of the sediment transport. The initial longitudinal profile consists of bed level steps at the transition of the reaches, calculated for the reference scenario. This was done in order to have continuous water levels and uniform flow for the reference scenario. The processes of adaptation of the bed, illustrated in the figure are described below:

1. The water levels will adapt instantaneously to the lower discharges, but the bed level does not respond as quickly.
2. The uniform flow depths in the reaches will be smaller. From the downstream free flowing boundary, the uniform depth translates into the downstream boundary for reach 3.
3. The downstream boundary for each reach is determined by the depth of the reach downstream of the considered reach.
4. Backwater curves will occur at the transition of the reaches, since the downstream boundary of each reach is determined by the depth of the reach downstream of the considered reach.
5. The backwater curves cause acceleration or deceleration of the flow, resulting in aggradation or degradation processes.
6. The gradient in velocity translates to a sediment transport, which will remain until the bed level has fully adjusted to the equilibrium slope, and there uniform flow is re-established.
7. This results in a new morpho-dynamic equilibrium.
8. For the bedrock controlled reaches, the slope is not changing in the equilibrium situation, although back water curves might occur at the end of the reach.

It should be noted that in reality the transition/bed level steps between reaches will be more smooth, resulting in a more gradual change of the bed as well. Furthermore, the Δz at the beginning of reach 3 might extend to reach 2, meaning that reach 2 can experience sedimentation on top of the bedrock, which is decreasing the slope.

The characteristic time scales for reaching the new equilibrium is calculated with formula 2.17 from Section 2.1.2. The length scale used in the formula is the length of the reach. And the corresponding sediment transport flux the flux calculated for the reference scenario (0.01363 m³/s). In this way, the characteristic time

Table 5.11: Bed level aggradation at the start of the reach for the new equilibrium scenarios $Q_{EFA, floodings}$, $Q_{EFA, maintenance}$ and Q95

	$Q_{EFA, floodings}$		$Q_{EFA, maintenance}$		Q95	
	Δz (m)	$\Delta z_{SI=1}$ (m)	Δz (m)	$\Delta z_{SI=1}$ (m)	Δz (m)	$\Delta z_{SI=1}$ (m)
1	106	39	232	113	893	505
2	120	46	263	131	1016	582
3	67	-7	270	84	914	373
4	1175	447	5861	3322	11896	7024

scale is calculated as the time it takes for half of the total adaptation to occur at the start of the reach ($L_{0.5}$). For reach 1 and 3 the calculated characteristic time scale is 1000 years, and for reach 2 and 4 this time scale is 5000-6000 years.

Explanation of the -7 in Table 5.11

The bed level aggradation calculated for reach 3, the EFA flooding scenario in case the river would fully straighten is -7 m. The interpretation of this negative bed level aggradation is explained as followed. The reduction of bed aggradation calculated in this method presumes that the plan form of the river will straighten. The aggradation will start again from upstream, however, before fully straightening of the river, the equilibrium state will be reached. In the hypothetical case of the new equilibrium state, the river would not fully straighten, but a sinuosity index of 1.12 would still remain, and the length of the river reach will be 36 km.

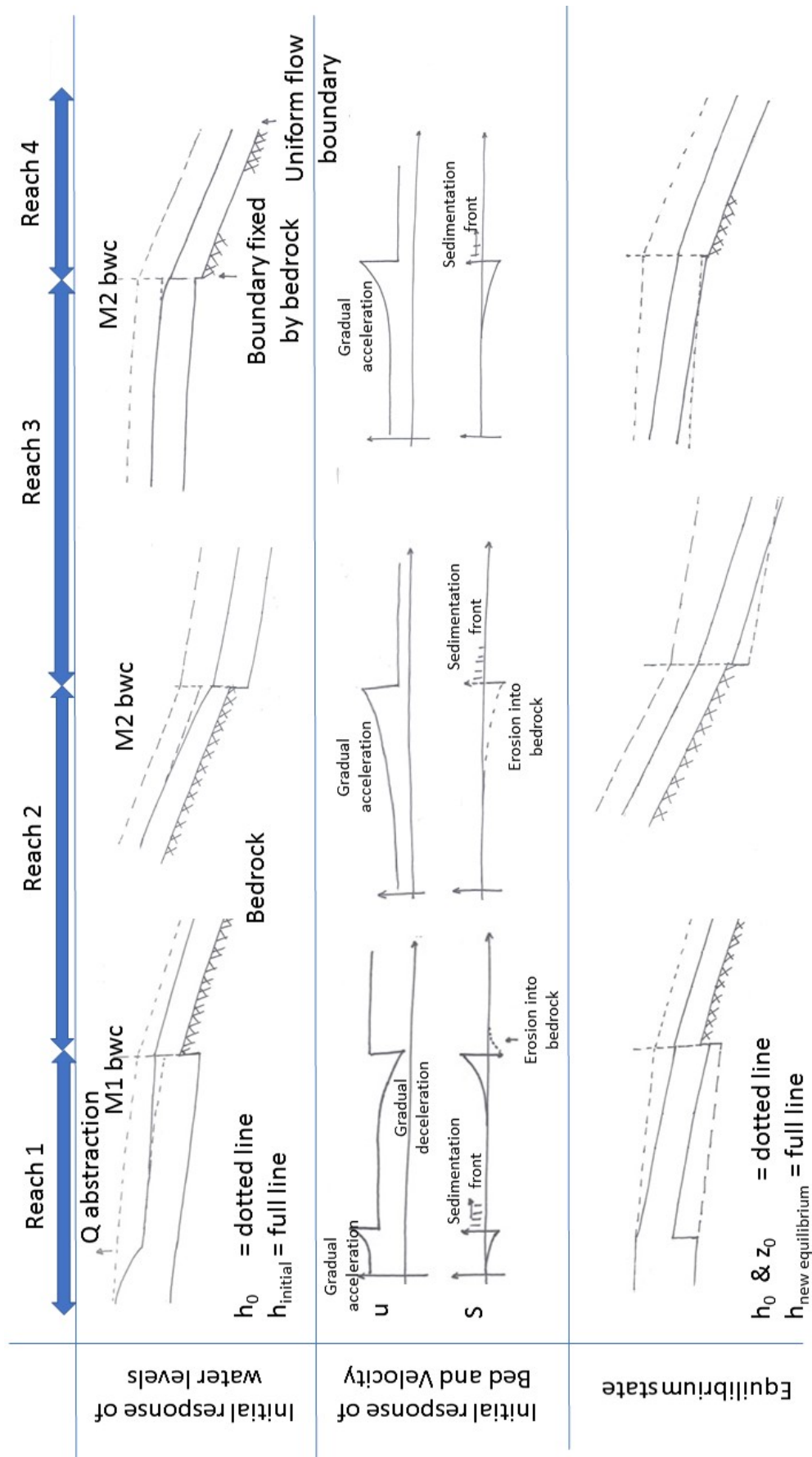


Figure 5.20: Initial responses of water level and equilibrium responses of water level and bed level for a lower discharge regime.

6

Discussion

In this chapter, the results of the assessments are discussed and put into a wider perspective for the morphology of the Mara River. First, the local assessments are discussed, where the difference of the results of the low- and high-flow field survey are described and the importance for ecology of different habitat is related to the ecological specialist reports. Second, the long-term results are discussed, both the outcomes and the four main assumptions that underlie the assessment. Last, a future perspective is provided, where the impact of observed processes not taken into account in the current modelling are qualitatively discussed.

6.1. Local assessments of representative sites (EFA assessments)

The local assessments of the EFA survey were focussed on the area around representative sites. Transects measured for the hydraulic survey are used for relating depths and velocities, and thus habitat coverage, to discharges Van der Waal, 2016. The morphological assessment focussed on assessing morphological features, which are mapped in the plan view and cross section figures (see Figure 5.7 to Figure 5.10), and the drivers of change for these features. The plan views provide clear overview of the habitat found at the sites, and the differences of low-flow and high-flow habitats. The morphological features are summarized in Table 5.7 and Table 5.8.

Looking at the differences between high-flow and low-flow coverage of channel features, it can be seen that during the low-flow assessment (discharges close to 95 percentile discharges, Q_{95}), coverage of flood benches and marginal zone is lacking. Less habitat coverage and habitat diversity and substrate diversity is covered, especially in the pool sites. At the riffle section turbulent and fast flow is present, but the area of coverage for these low discharges is very small.

At sites with bedrock, more diversity in the hydraulic habitat is found (Mara Purungat, Mara Beef). The bedrock influences the roughness of the channel, which influences the turbulence and velocity of the water flow. Between bedrock outcrops a diverse range of sediment sizes get can settle in pockets, providing good habitat for fish and macro-invertebrates when inundated. However, the coverage area between the bedrock is very small.

In the more alluvial parts, the hydraulic habitats found are less diverse, looking at the velocity-depth graphs. The substrate is expected to be less diverse in alluvial areas, but this cannot be justified with data because to accessibility problems due to wild life present at these sites. Generally, the diversity in the alluvial parts comes from the shape of the cross section, with flood benches and higher elevated areas. In the Mara River, the alluvial reaches are quite incised and therefore less diversity is found over the cross sections (Mara Purungat Pool, Mara Emarti Bridge, Govenors Camp). High flows will be confined between the incised riverbanks, exerting high shear stresses on channel banks and hampering flood bench formation and diversity in the cross section. The diversity found in the incised alluvial parts expresses itself in the fact that the outer bends of the meanders are deeper as river bed scour occurs, whereas inner bends are shallower, where depositional areas are found.

The tributaries show more diversity and stability over the cross section while being mostly alluvial (Purungat tributary, Sand). In the Talek and Purungat tributary incision was also visible. The vegetation coverage is also

better, and flood benches were more stable and vegetated with grass.

The differences in diversity and stability of the habitat provided by the morphology over the river is important for fish, macro-invertebrates and vegetation. Comparing the habitats summarized in the habitat tables, velocity-depth graphs and plan views with the ecological surveys (Masese, 2016, O'Brien, 2016, MacKenzie, 2016), it can be concluded that the habitat found in the main stream of the Mara is undermined by its diversity due to incision. Substrate diversity and cross sectional diversity can be better as flood benches with vegetation as refuge area are absent from the main stream of the Mara. The tributaries (with the exception of the Talek) show more diversity and cover area, which provide good spawning areas for fish. It is therefore noted that the morphology plays an important role in the longitudinal connectivity of the Mara river, allowing migration of fish between the tributaries and the main stem.

6.2. Long term morphological analyses

The long-term river scale analysis is focussed on linking the sites together and, with the help of sediment transport principles, the stability of the bed is assessed. The river-scale model was able to determine cross sectional averaged changes in indicators as bed level change, average depth and velocity, based on the assumption that the alluvial reach is leading for sediment transport. The results of the calculations will first be discussed and the assumptions underlying the calculations are explained in the second part of this section.

6.2.1. Results of long-term analysis

The sediment transported calculated for the current situation is in the same order of magnitude as the Tana River (located on the east side of Kenya) and the Sabaki river, discharging its water and sediment into the Indian Ocean. The sediment loads for these rivers are respectively 6.8 million ton/year, which is 6 times as large as the Mara river, Geeraert et al., 2015 and 7.5 - 14.3 million ton/year, which is 7-14 times as large as the Mara river, Katwijk et al., 1993. As said, the order of magnitude is found reasonable, since the Tana and Sabaki river discharge much more volumes of water.

The corresponding bed level raise at the beginning of the reach seem unrealistic high, although this should be seen in the perspective of changes over the characteristic time scale of adaptation, which is 1000 years. For the extreme case of a discharge regime according to Q_{95} , the slope of the meandering part would increase by a factor of 15 compared with the reference conditions. In this scenario, not only the habitat would severely be changed by sedimentation, but also it would be likely that the sinuosity of the river will change, resulting in a straightening of the river. Linking this outcome with the habitat observations during low flows, it is noted that also the habitat coverage during Q_{95} is expected to not sustain enough suitable habitat for fish migration and recruitment. Therefore, it is evidence that an EFR based on only Q_{95} will not fulfill the aim of providing suitable habitat for a healthy ecosystem. $Q_{EFA, floodings}$ showed an increase of slope with a factor 2, which is much less, however, over the distance of a reach it still results in large bed level increase numbers.

It must be realised that the results of the analytical calculations are only an indication of the trend of morphological responses of the river bed. The results only give a trend and cannot be used quantitatively. Not only the results are not calibrated and validated, but also 1-dimensional and 2-dimensional processes are not taken into account in the calculations. The factors influencing the uncertainty about the results, are discussed in the next section, 6.2.2.

6.2.2. Interpretation of the assumptions

Four main assumptions are distinguished, and their impact on the results is discussed below.

1) Representation of the river geometry

The differences between the geometry of the reaches were high, mainly the bed slope derived from the STRM data. This led to large numerical artefacts at the transition of reaches. It can be concluded that the simplification of the river was too coarse to model it properly. The scenario based approach for the numerical modelling was supposed to cancel out numerical artefacts by only looking at differences between the scenarios. Unfortunately the numerical artefacts encountered were so large that scenario modelling was not

possible within the simplifications that had been made based on data availability.

Comparing the simplifications made for the geometry of the river with other one-dimensional sediment transport model for the Yellow river in China, it appears that the data resolution used in this research was indeed small. Kemink Kemink, 2002 set up a numerical sediment transport model for a reach of 300 km of the Yellow river. Kemink used data of 30 cross sections along the river stretch for the modelling of 1-dimensional sediment transport processes. In this research, 4 cross sections are used to represent 200 km of the Mara river. Also Kemink only concludes on the qualitative aspects of the research, not putting much value to the quantitative results.

2) Estimation of the sediment transport flux

The estimation of the sediment flux is based on the alluvial meandering reach. The sediment flux is calculated assuming that the river would be in equilibrium morphological state. Together with the assumption that the sediment transport in the alluvial reach is leading for sediment transport, this means that the flux of sediments only needs to be calculated for this section. The sediment transport formula used was the Engelund-Hanssen formula. This was found reasonable since the sediments in this part were classified with a representative grain size within the range of the Engelund-Hanssen formula and the settling velocity was smaller than the shear velocity for the representative discharge. The assumption that the sediment transport in the other reaches is supply limited is verified by calculating the transport capacities for other reaches and comparing the fluxes with the transport capacity of the alluvial reach. The capacities for the other reaches were higher than the transport capacity in this reach, meaning that the assumption was found to be correct, and the capacity of the alluvial reach defines the amount of sediments being transported.

Although for the alluvial the formula of Engelund-Hanssen and the sediment transport principle seems to work out fine, the sediment transport calculations in the other reaches are questionable. This is because Engelund-Hanssen is meant to calculate sediment transport in purely alluvial rivers. Local processes like selective transport and non-uniform flow governing the sediment transport in bedrock and mixed sediment reaches are not further looked into in this research, although these processes are very important for the ecological habitat.

3) Inflows from tributaries

The inflows of the Sand and Talek tributaries for sediment and water are highly simplified in the analysis. The sediment flux from these tributaries is assumed to be zero, since no data is available on the sediment flux these tributaries deliver. The discharge is relying on hydrological model of Hulsman Hulsman, 2015.

In reality the tributaries are discharging sediments to the main stream. Hulsman Hulsman, 2015 even concluded that the Sand catchment delivers by far the most of the fine sediments to the main stream Mara. From satellite images, it can also be seen that many inset and lateral sand bars are present just downstream the confluence of both the Talek and Sand tributary with the Mara River. These features confirm that the Sand and Talek tributaries deliver a significant bed load sediments as well to the Mara river.

Sediment contributions from the tributaries have a considerable impact on the river morphology. The Sand and Talek tributary are expected mainly to be delivered during flash floods. During these flash floods, a lot of sediments are delivered to the main stream of the Mara. The main stream could also have a high discharge, but as the flash flood recedes quickly, the sediments will settle downstream of the confluence, creating the inset and lateral deposits visible on the satellite imagery from Google Earth. The inflows of much sediments could be the cause for the increased slope downstream of the Sand tributary.

4) Representative discharge

The analytical calculations were performed with a constant, representative discharge, considering that the seasonality would be simulated in the numerical model. The constant, representative discharge is proven to be useful in different studies Wang et al., 2008, however, De Vriend de Vriend, 2015 explains that the representative discharge for the estimation of the bed slope is too simplified of an assumption. For the first estimations of the sediment flux, the assumption of the representative discharge is thus found to be valid, but for the translation to the difference in equilibrium slope, numerical modelling should be used to verify the analytical calculations and to include the seasonality of the discharges, and simulate the bed level changes. For the Mara River basin, the discharges can vary highly between low- and high-flow seasons. The monthly

average discharge modelling for the reference scenario shows that the discontinuities at the transition of the reaches are creating large responses of the bed level. This is related to the simplified and coarse representation of the bed slope and the large responses are considered as numerical artefacts.

6.3. Mara River in future perspective

Although the bed level of the Mara river can be stated to be stable over the coming years, when extending the time scale even further also other processes become important that might influence the sediment balance in the river. For this purpose, the incision character of the river will be discussed with respect to the hypotheses of Rowntree, 2016, and also considering channel evolution theory of Simon and Hupp. Lastly, the implications of the construction of dams will be discussed.

6.3.1. Incision character

Historical causes

Rowntree formulated two hypotheses about the cause of the incision of the channel. These are both based on natural disturbances. Both the hypotheses are discussed here, and suggestions are made to verify the hypotheses. Calculations based on sediment transport principles could be able to identify if the incision process is reaching its end or if it is proceeding. But the results from this research do not provide the opportunity for comparison to these hypotheses.

The first hypothesis is that, the large flood (El Niño 1876-1878) after a long period of drought (post Little Ice Age 1800-1850) caused the incision seen up to date. A shift to a much larger discharge regime, together with a lower resistance of the channel due to die back of vegetation describes the key elements of this scenario. In Equation 2.11 it can be seen that if it is assumed that the width, representative grain size and sediment transport stay constant, the slope of the river will reduce to reach equilibrium transport again. Hereby the assumption that the discharge of water will be proportionally larger than the discharge of sediments has to be made. The reduction in slope then can only be reached if the upper part of the reach would incise. The reduction in slope could be calculated with Equation 2.16, where ΔQ is then negative, representing extra discharge instead of water withdrawal. However, neither the change in discharge between the two hydrological periods nor the difference in equilibrium slopes is known. With a proper working numerical model several scenarios could be tested and compared with the time scale (140 years) and the rate of incision throughout the channel (+/-10 m).

The second hypothesis is related to a tectonic shift of the Siria fault, close to the river at Mara Kichwa Tempo site, (see Appendix A). In this case, the slope of the river is expected to have steepened, which will increase the transport of sediments (Q_s). Erosion will start from upstream travelling downstream, until the equilibrium slope is reached again. Difficulties on the quantification of this hypothesis is that uplift can go together with the incision, and can continued process. Also there is no evidence about when such a movement of tectonic plates could have happened.

Future predictions

In addition to bed lowering, the incision of the river also shows signs of channel widening by unstable banks and slumping banks. Signs of channel widening are most evident around the Purungat Bridge riffle section. River widening is not being taken into account in this theoretical analysis, even though the site assessments showed clear signs of bank slumping caused by mass wasting. Widening of the macro-channel could involve the establishment of new flood benches, increasing diversity of habitat and refuge area for fish and macro-invertebrates during high flows. Also, the impact of hippopotamus on the flood benches and connectivity with the terraces with the main channel is present, but difficult to predict.

Considering the evolution of the river in this perspective gives new insights, contributing to the understanding of the future morphological shape of the river, if it is still incising or only widening.

Langdoen et al. has developed a numerical model (CONCEPTS) which can reproduce these processes, with minimum data requirements Langendoen and Alonso, 2008. On top of the data required for one-dimensional sediment transport modelling (river geometry, roughness, boundary flows of water and sediment, grain size), bank stability data is needed in the form of soil shear strength, bulk soil weight and elevation of phreatic surface. For the predictions of the channel geometry in the Mara River, this would also be a good option, since

the incised banks and widening are observed.

6.3.2. Impact of proposed dams

The feasibility studies of a dam, Nile Basin Initiative (NBI), 2014, focussed namely on the economic aspects of three proposed dams. In total, the dams would have a volume of 150.8 Mm³, whereas the mean annual run off is more than 1 billion m³. Two of these dams, with a storage of 41 Mm³ would already supply enough water supply for the whole Mara River Basin Peyroche d'Arnaud, 2015. The storage of the dams would cover only 1% of the mean annual run off, which implies that the discharge peaks in the Mara river will still remain. As the prospects of the Mara river are that during the long rains, the floods will always happen, the morphology in the river is not being endangered. The floods will counteract sedimentation during the low flows, and also be able to mobilize the bed substrate and winnow the fines for ecological purposes.

Negative effects of the construction of dams are large ecological impacts on the habitat connectivity, of the river, and morphologically, sediment continuity de Vriend, 2015. The water leaving the dam reservoir has a reduced sediment load, therefore the water will pick up sediments from the downstream side of the dam easily. Impacts on the ecology are armouring of the bed and possible scour of flood benches and sand bars just downstream dams. This is reducing the habitat variability and suitability.

The Tenwek dam, a small hydropower dam facilitating the Tenwek hospital located along a natural waterfall in the Nyangores river, also experiences filling up of sediments. The reservoir needs to be dredged ones every few years.

Conclusion and Recommendations

In this research, the influence of changing flow regime on the morphology for the Mara River Basin is assessed in perspective of the establishment of the EFRs. This research contributed to:

1. The morphological characteristics of the Mara river, solving research question 1;
2. Assessing the longitudinal stability of the Mara river with sediment transport formulas. In this long-term and large-scale assessment, the results from reference scenario based on the current parameters of the river were compared with future scenarios for discharges conform the EFR. By these means, the second and third research question are solved;
3. Reflecting upon the assumption taken in the EFA that the cross section of the river stays stable, and thereby answering research question 4.

The conclusions on these research questions are respectively given in the subsections of Section 7.1, followed up by the recommendations in Section 7.2.

7.1. Conclusions

7.1.1. Morphological characteristics of the Mara river

Incision is one of the main characteristics of the Mara River, which is apparent at alluvial section throughout the river. This incision limits the connectivity with the floodplains and terraces. The flood benches are scoured or discontinuous, explained by the fact that the high flows are not attenuated by the floodplains, but rather confined within the main channel because of the disconnection with the floodplains. The variability of the ecological habitat is therefore undermined and recruitment of marginal vegetation as refuge area for fish is more difficult. The 2-dimensional process of meandering by scouring outer bends and depositing on the inner bends is the most important factor which defines the limited habitat diversity in these meandering sections.

The incision of the river also results in instability of river banks, being subject to bank slumping. These observations give cues that the basin is experiencing river widening, which is a process of channel evolution over long time scales. The river basin would actually benefit from this process since channel widening would provide opportunity for flood benches to re-establish and therefore more diversity in the cross-sectional area and habitat would be available for fish, vegetation and macroinvertebrates.

Also, sections under influence of bedrock are identified. The elevation difference between the high Mau Forest and Lake Victoria is mainly overcome by the bedrock presence, as can be concluded from the comparison of geological maps and the elevation profile. In bedrock sections incision of the channel is hampered by resistant bedrock, but the channel is wider here. Sediments transported during high flows are stored in the recession limb higher up the cross section in sand bars. The bed is mainly made up of cobble or boulders over bedrock. The roughness of the bedrock and its resistance to erosion cause a lot of turbulence, and fast flowing habitats. Sediment that is being transported can be assumed to be supply limited, although sparse sediment pockets can be found in between bedrock outcrops. Marginal vegetation in these reaches is found along the sand bars, a bit further up the cross section. Cover features for fish and macroinvertebrates are lacking in these sections.

Compared with the main stream of the Mara, more habitat diversity and cover area like flood benches are

found in the tributaries. Also the substrate condition offers good spawning area. As these areas are not well represented in the main stream of the Mara River, connectivity between the tributaries and the main stream is found to be important for fish to migrate and recruit in the main stem.

7.1.2. Stability of the Mara river

Reference scenario

Based on the site visits the incision and flood bench erosion give the signs that the river has been eroding at the alluvial sections, together with the river evolution evident from satellite imagery. However, the bedrock presence throughout the river seem to keep the channel from eroding.

In the large-scale analysis, the sediment transport capacity for the alluvial reach is comparable to other rivers in Kenya. The bedrock sections can be seen as under supplied reaches for the simplified representation of the river, meaning that the sediment transport in these reaches are governed by the incoming sediments from upstream. The first indication for the characteristic time scale of adaptation to perturbations based on reference conditions is around 1000 years. Bedrock dynamics is not expected to shorten this time span.

Although the research aimed to give an indication of the quantification of the sediment transport processes, care should be taken with the interpretation of the outcomes. Due to limited data availability, the river was too simplified to perform proper numerical calculations. The verification and calibration of the analytical calculations still remains. In the next section, 7.2, recommendations are given to improve the estimation of the sediment flux and characteristic time scale of adaptation.

EFR scenarios

Generally, as discharges decline, the slope of a river responds by steepening, as sediments from upstream no longer can be transported and are settled upstream. For the Mara River, in the bedrock reaches the slope is expected to stay the same, as the sediment transport is supply limited at these locations. For the meandering reaches, the difference between the equilibrium slopes of the reference and EFA scenarios is quite big. Discharge scenario of Q_{95} shows a drastic increase in slope (16 times higher than the reference scenario), resulting in aggradation of the bed elevation at the start of a reach. This was actually expected, as discharges decline greatly while the incoming sediment flux stays the same. The $Q_{EFA, maintenance}$ scenario also showed large increase of slope, namely increasing with a factor 5. These results together with the fact that local habitats which can be expected with Q_{95} are not supporting enough suitable habitat for a healthy river system (coverage and opportunities for migration). This indicates the importance for the establishment of an EFR and the importance of including the morphological assessed flows for annual floods, for maintaining of a healthy ecosystem. For these results also the characteristic time scale of adaptation must be taken into account, of 1000 years.

The results of these calculations can be improved by downscaling the assessment, as discussed in the Recommendations section.

Applicability of the sediment transport principles in the Mara river

The sediment transport analysis in this research is based upon alluvial transport, which was valid for the alluvial reach. This reach is also the most dynamic, considering its plan form changes and incision character. This implies that analysis of this reach with respect to sediment transport is most important. For the other reaches, bedrock is governing the stability, and bedrock dynamics, is important there. The interaction between the transport of the alluvial layer with the underlying bedrock is described by other mechanisms. Since the time scale of the processes for incision in bedrock are much larger, the assessment of stability of slope of the bedrock reaches this was not investigated in this research. For ecology, selective transport processes are very important to take into account, as they define the state of the substrate, which is important for fish habitat.

7.1.3. Consequences of the outcomes of the long-term analysis on the EFA methodology

Considering the large characteristic time scale of adaptation calculated in the long-term large-scale analysis and the time scale of EFA management cycle of 5 years, it can be concluded that the assumption that the geometry of the river stays the same is valid for the Mara River.

Another important consideration for this conclusion is the fact that the calculated future slopes are related

to a flow regime which is strictly following the EFR. Yet it is recognised that in the case of the Mara River, the high flows during the long rains will be occurring whatever will happen in the basin. Abstractions without constructed dams will have its main impact during the low flow season, as water is scarce during those times. And even when dams will be constructed, still the high flows will occur due because the storage of the dams is only 1% of the mean annual run off in the basin. The persistence of high flows will keep the equilibrium between aggradation and erosion.

The morphological changes that might have occurred in the river are assessed based on the state of the features during the field work. This means that it is not needed to put all the efforts in collection of more detailed data and modelling exercises. The Geomorphologic Assessment Index (GAI) assessment is considered as the best possible method for the assessment of the morphology in the circumstances of limited data availability for morphology together with a short time frame assessments.

7.2. Recommendations

Although it can be concluded that for the 5-year EFA management cycle the assumption that the river bed is stable can be held, still it is important to look into the temporal behaviour of the predicted adjustment. A time scale of adaptation of 1000 years is long, and insight into the evolution of the adjustments on the short term would offer more confidence for the conclusion. This can be done by improving the numerical model, with the aim to simulate daily discharge forcing of different scenarios. A list of recommendations to undertake for improving the numerical model is given in Section 7.2.1, together with the data that would be needed. In Section 7.2.2 recommendations are made on how to include 2-dimensional processes into long-term assessment of the morphology.

7.2.1. Improvement of the numerical model

Improvements on the 1-dimensional numerical model should be aimed at perceiving the temporal behaviour of responses of the alluvial bed. Improvements recommended for this purpose, and a suggested approach for implementing the improvement are:

1. Including the incoming sediment fluxes from the Talek and Sand tributaries.
Approach: A first estimation can be based on the sediment transport capacity of the tributaries calculated with the hydraulic parameters measured at representative sites for alluvial transport. For these tributaries it is important to simulate with daily discharges because they have a flashy character. To verify these estimations sedimentation and erosion patterns just after confluences of the tributaries with the main stream should be analysed from satellite imagery. can be undertaken to estimate the amount of sediment the tributaries bring in. These estimations can be compared to the fluxes of the first estimation for validation.
2. Dividing the reaches into smaller reaches and make the transitions from reach to reach smoother.
Approach: Split reach 1 up into two reaches. Split reach 3 up into two reaches, one upstream of the confluence with the Talek, and the other one downstream of this confluence. Also reach 4 also needs to be better represented, by both the steep as the flatter parts of the reach. Representative sites for this reach need to be visited for this purpose. The next level of modelling will be reached when time and effort is put into the establishment of a more accurate DEM by for example by extensive DGPS measurements, 3D photography or airborne Lidar measurements.
3. Improving the behaviour of bedrock in the numerical model.
Approach: A less (or none) erodible layer should be applied in the model. Additionally, the storage capacity of the pockets should be considered and estimated to prove if the assumption of the under supplied reach is valid. Measurements of the thickness of the alluvial layer at representative sites can add value about the maximum incision of the alluvial reaches.
4. Applying daily discharges as hydraulic boundary.
Approach: Daily discharges from the hydrological model of Hulsman over 20 years can be used. For the EFA scenario daily discharges should be chosen conform the averaged discharge and flood events of the EFRs.

5. Including selective transport processes which are important for the ecological habitat.

Approach: Application of a two layered sediment transport model, which distinguishes between a transport layer and a storage layer with both different grain size distributions. Data on the substrate characteristics should be used for this purpose. But it must be realised that the diversity of the substrate over the cross section was clearly be seen, therefore, a good interpretation of this process will be difficult.

7.2.2. 2-dimensional morphological factors

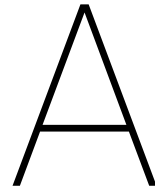
The 2-dimensional morphological factors of channel widening and meander cut offs are not explicitly included in the analysis for long-term morphology. While in the long-term perspective, they might have equally important effects on the change of ecological habitat. It is recommended that the evolution of the channel in this perspective is being monitored. Meandering of the river is already analysed by assessing areal photographs and satellite data by Murunga (Murunga 2017). Next steps will be to monitor the channel widening. Building up a record of morphological data is important to be able to calibrate and validate morphological models. Standardizing the data collection during the EFA surveys is therefore recommended. Data in the same format over a long time span for the same representative sites along the river will contribute greatly to future assessments and understanding of the river. As also is being recognised already in the adaptive management and monitoring plan of Zielinski, 2016. For the morphological part it is recommended to include quantitative information about specific morphological features and their extend by mapping them on a plan view (best to do during low flow), cross section measurements and substrate characteristics. This both enlarges the confidence of the assessments and confidence in habitat diversity evolution.

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Analytical calculations

In this appendix, the calculations are summarized and explained. First, the simplifications of the river are explained. Next, the formulas used and calculations made are shown, in tables.

1. Spatial representation of the river
2. Representation of the discharge to do calculations
3. Sediment transport calculations
4. Determining river parameters; D_{50} , n
5. Calculate scenarios; change of slope between equilibrium states, and characteristic time scale of adaptation

A.1. Simplifications in geometry

The first step of doing manual calculations, is to represent the river in such a way that it is possible to do calculations by manual. The river has to be represented in a simple, schematic way. This is done by dividing the river longitudinal into segments, make a simplified discharge profile, make a general cross section for the river. Once the river can be represented in this format, the calculations can be done.

A.1.1. Elevation profile

From Mara Mines, the river can be characterised as a flood plain ecosystem, where the width in this part is 80 m and the floodplain is dominated by grassland and shrub vegetation. The riverbed consists mostly of fine clay, and sediment deposits along the river banks can be seen (sand bars). The last part, of about 50 km upstream Lake Victoria, is a swampy wetland (Ndomba, P.M. and Mtamba, 2012). Until some 25 km downstream of Mara Mines, along the river in almost every bend, lateral sand bars can be identified on Google Earth. Also clearly agriculture is seen around the river. More downstream, the river banks are covered with forest, and no sand bars can be found on the satellite data of Google Earth. This is the part where the river enters the swamp, 25 km downstream of Mara Mines.

Just upstream of Mara Mines, the slope increases almost by a factor of 10, the width of the river stays the same, but the channel bed is dominated by coarse sand and cobbles. On the satellite imagery of Google Earth an active river is seen, with riffles and rapids and also vegetated flood benches inset and lateral. Even a small braided section can be distinguished. These observations correspond with the increase in slope of the river over this reach. The part where the active river is seen, is indicated with the purple line in A.2.

Upstream of the boundary between Tanzania and Kenya, the river enters the midland plains area, with the Loita plains and Siana plains in the East Figure A.1. Here the slope is more gradual. Still a sequence of pool-riffle can be seen here (verify with Google Earth images!!). For the Purungat site, mainly bedrock was found over riffles, with large lateral sandy flood benches, and pool areas with finer material.

At the upstream part of this reach, actively eroding meanders are found over several satellite images originating from different years of Google Earth. The energy needed for this dynamic behaviour could originate from

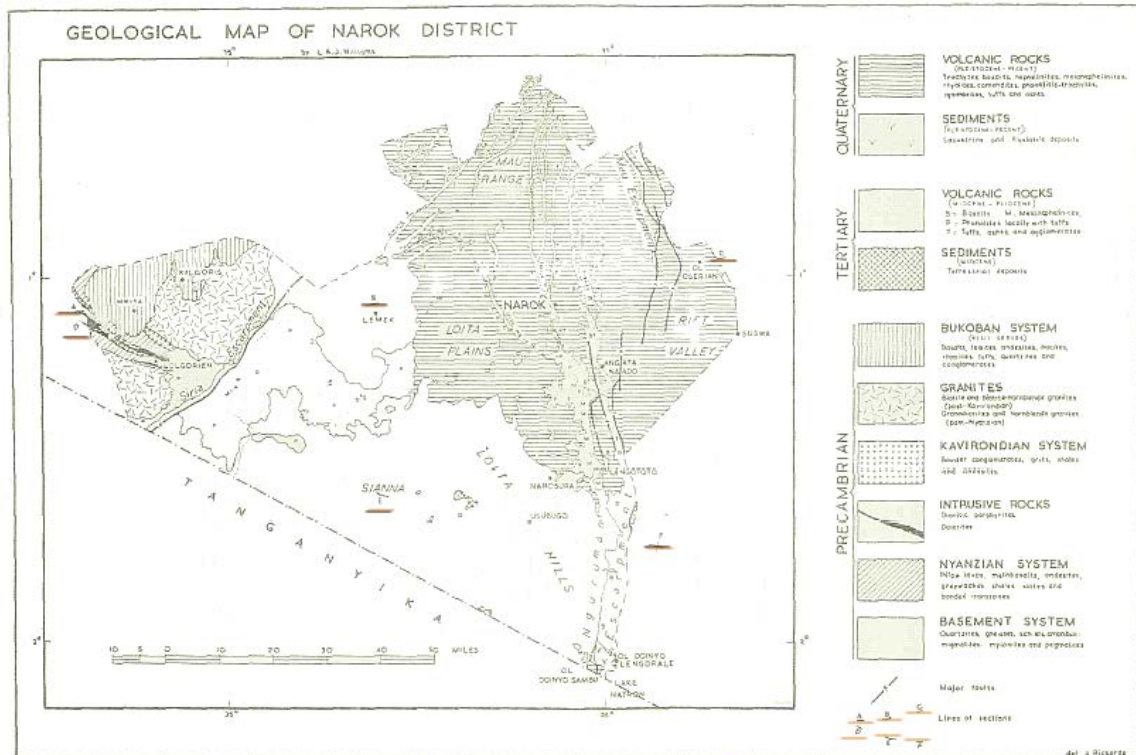


Figure A.1: Geological Map of Narok region from Glover and Williams 1966.

the steep part upstream of the meandering part, around Mara Kichwa Tempo. This change in slope is very sudden, and might originate from geological layers which are less erodible. Also, in geology it can be found that around Mara Kichwa Tempo, the Siria fault is very close to the river. See Figure A.3 A fault means that there must have been movement in the earth's surface in the past, and since it is so close to the Mara River at Kichwa Tempo it could have affected the slope of the river there. Also the geology map of Dutton 2012 reflects that just upstream of the meandering part, a granite layer is detected, and in the meandering part the more erodible basalt Rowntree 2016 is present.

Upstream of the reach around Mara Kichwa Tempo, a more gentle slope is found again, comparable to the gentle slope downstream of the steepening. This part is the most upstream part of the river that will be taken into account for this study. We start at Emarti bridge, where incision is very visible. The banks here are some 10 meters (see Technical report fieldwork). The geology map of Dutton et al. 2013 shows here that the riverbed consists of fluvial material overlying basalt and serpentine, which can be classified as more easily erodible again. A few kilometres upstream of Emarti the confluence of the Amala and Nyangores is found. More upstream the mountain zone can be classified, where the river is much steeper, and mainly boulder and cobble is found at the riverbed. Small floodplains are identified, and a lot of small holders fill in the land cover here. This land use continues till a few kilometres downstream Emarti bridge, where we also find a few big pivot plots.

A.1.2. Cross section

The cross sections of Mara Beef (just upstream Mara Emarti Bridge), Emarti Bridge, Mara Kichwa Tempo, Mara Purungat Bridge and Mara Mines are plotted in Figure A.4.

In Table A.1 an estimated width and depth for each profile is given. The data for the cross section of Kogatende we rely on measured data from the EFA survey in 2007 (Ndomba, P.M. and Mtamba, 2012). The measured profile complies with their literature review, where the expected width of the river in the lower reach is 80 m. The measured width at Mara Mines is however much smaller, and constraint to 50 m. This could be caused by the fact that we were measuring in a pool section, just behind a large riffle section where the width of the river was much larger. Although, the cross sections measured by Ndomba, P.M. and Mtamba 2012 have the same width. So there must be another cause why the river width at Mara Mines is smaller than the width

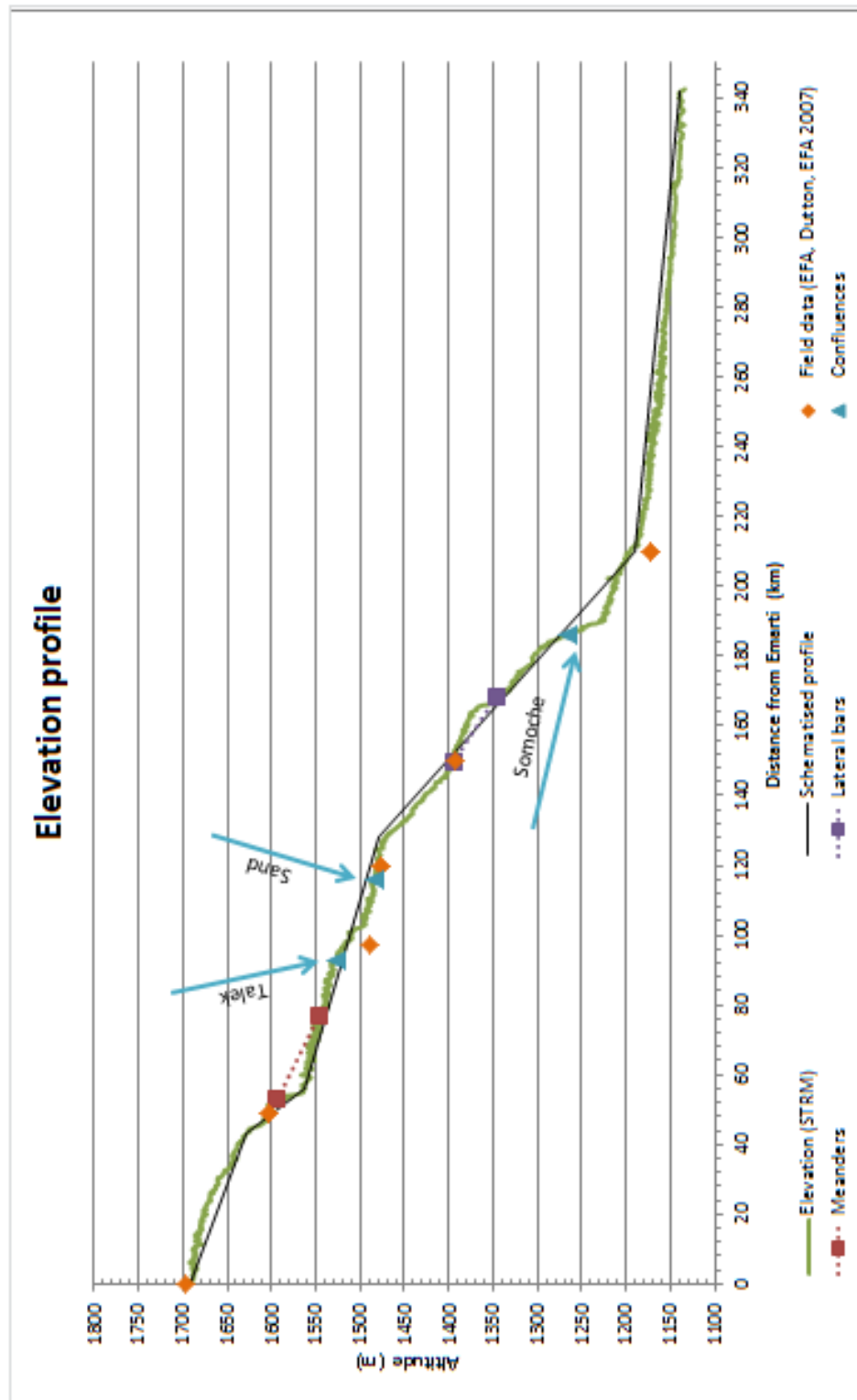


Figure A.2: Elevation profile of the Mara River with characteristics and schematised profile

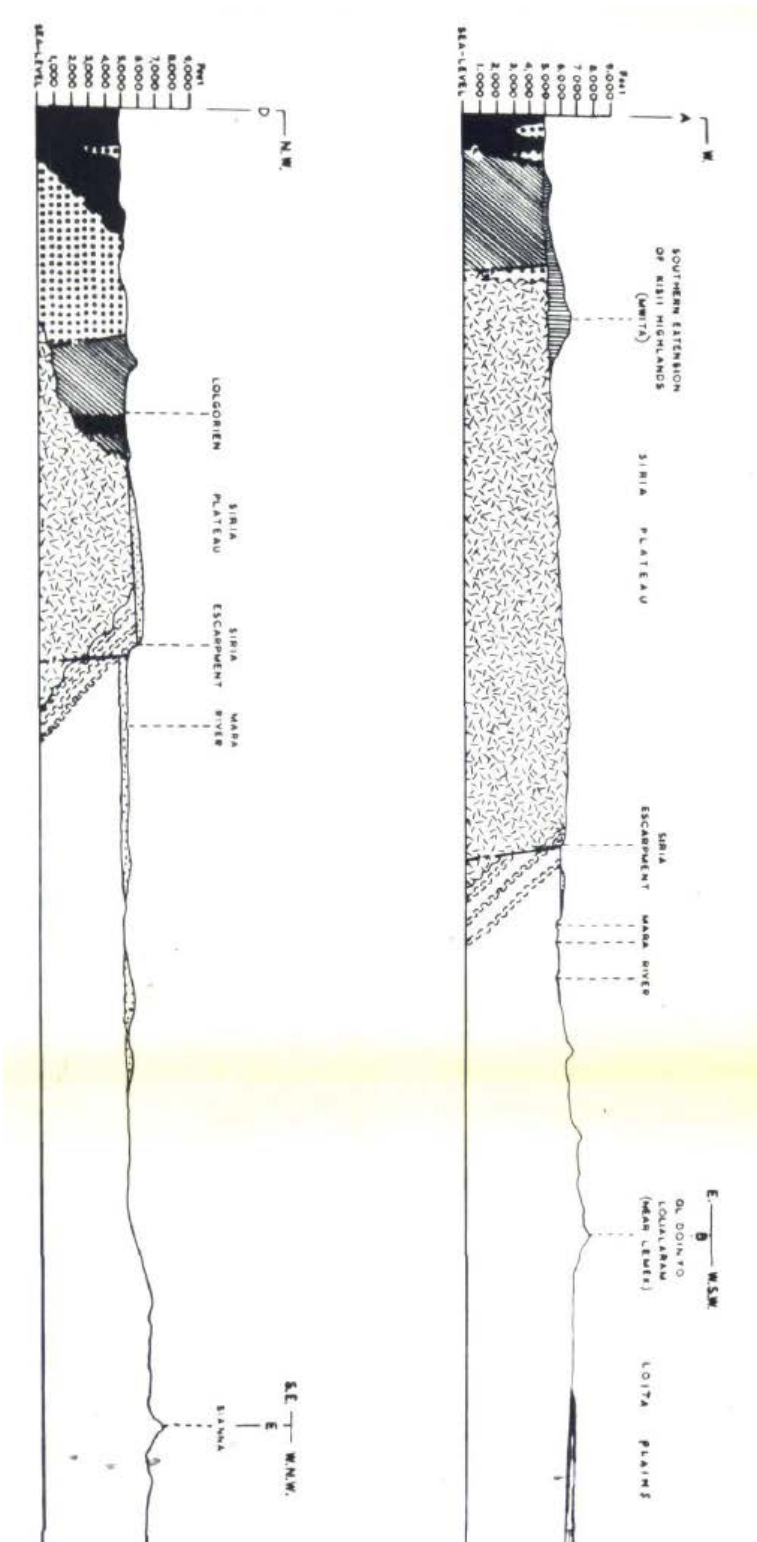


Figure A.3: Detail of the cross sections A-B and D-E from historical data from Glover and Williams 1966

at Kogatende. For Mara Purungat, it clearly can be seen that the pool section has the same width over each depth, and that the riffle section is more trapezoidal. The cross section of Mara Kichwa Tempo is similar to the cross section of Mara Purungat Riffle. In comparison with the other cross sections, it clearly can be seen from the top left figure that at Emarti the river is most severely, incised for approximately 8m (considering a normal depth of the channel of 4 m).

In the part downstream of Mara Kichwa Tempo, where the river is actively meandering, Rey et al. 2015 measured discharge and cross section of the river in 2014; in the upper part at Little Govenors Camp and at Mara Serena pumphouse. At both locations the river was 22 meters wide, but at Serena pumphouse, there was a 6 m shallow flood bench on the left hand bank.

Representative Site	Reach	Width (m)	Depth (m)
Mara Mines	LV-MM	60	7
Mara Kogatende	MM-MP	60	7
Mara Purungat	MP-MKT	39	6
Mara Kichwa Tempo	MKT	45	5.5
Mara Emarti	MKT-EM	27	12

Table A.1: Schematised cross section per site

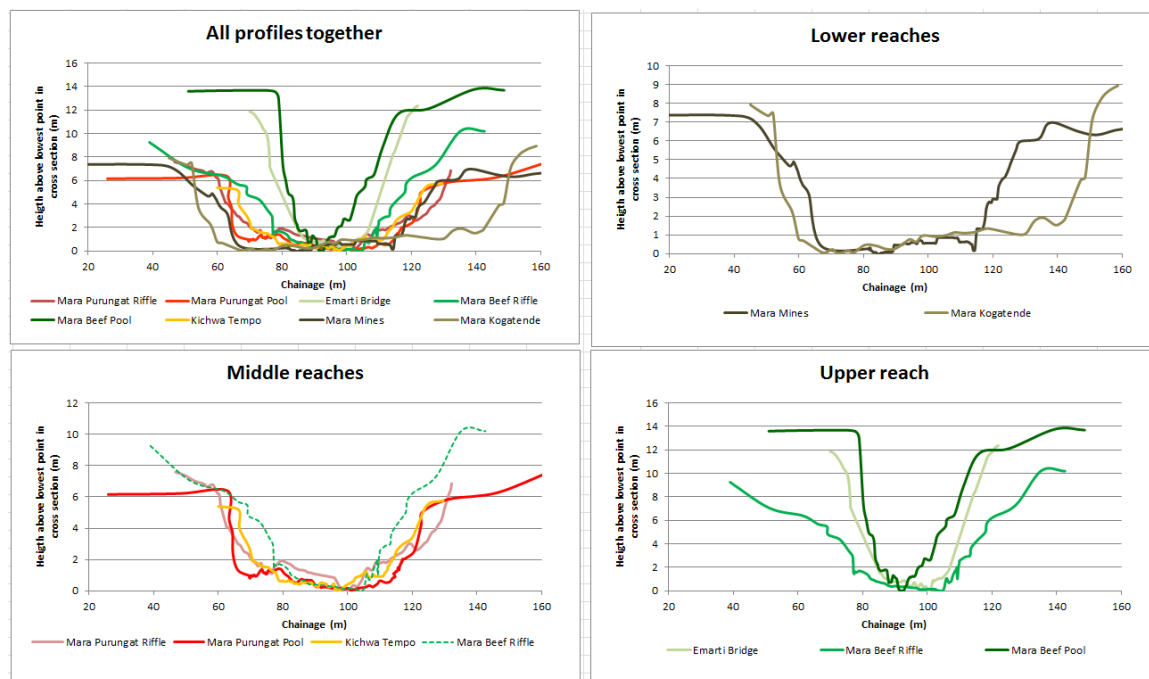


Figure A.4: Cross sectional profiles measured along the river during field survey in 2015 and 2016. The profile for Kogatende is obtained from Muthike et al. 2007b.

A.1.3. Discharge

The discharge records from the hydrological model of Hulsman, 2015 are used. These records include discharges all days for all outflows of the sub basins (see Figure A.5). The WRMA data contains limited discharge records for the Sand and Talek, and also sometimes days are not included. The data for the timespan October 1970 - October 1994. These daily discharges are converted to representative discharges for the sediment transport calculations. This resulted in the following discharges:

The EFA discharges are also

Reach	Discharge
Emarti - Kichwa Tempo	34.4
Around Kichwa Tempo	34.4
Kicha Tempo - Mara Purungat Bridge	39.9
Mara Purungat - Mara Mines	83.1



Figure A.5: Subcatchments defined in the hydrological model of Hulsman, 2015.

A.2. Calculations

A.2.1. Representative discharge

Eventually, the representative discharge is chosen to be based on the hydrological modelling from Hulsman, 2015. This is because these also include the inflows of the tributaries.

The representative discharges for the current state are calculated with the following equation;

$$Q_{representative} = \sum p(Q_{w,k}) * Q_{w,k}^{(b/3)} \quad (A.1)$$

Table A.2: Representative discharges for different scenarios. Where $Q_{EFA2016}$ is the discharge recommended without taking into account the freshest and yearly floods, and $Q_{EFAfloods}$ taking into account the freshest and the yearly and 5-yearly floods.

Reach	$Q_{current}$ (m ³ /s)	$Q_{EFA2016}$ (m ³ /s)	$Q_{EFAfloods}$ (m ³ /s)	Q_{95} (m ³ /s)
1	34.4	6.9	12.2	2.1
2	34.4	6.9	12.2	2.1
3	39.9	8.0	20.0	2.8
4	83.1	8.9	31.26	4.7

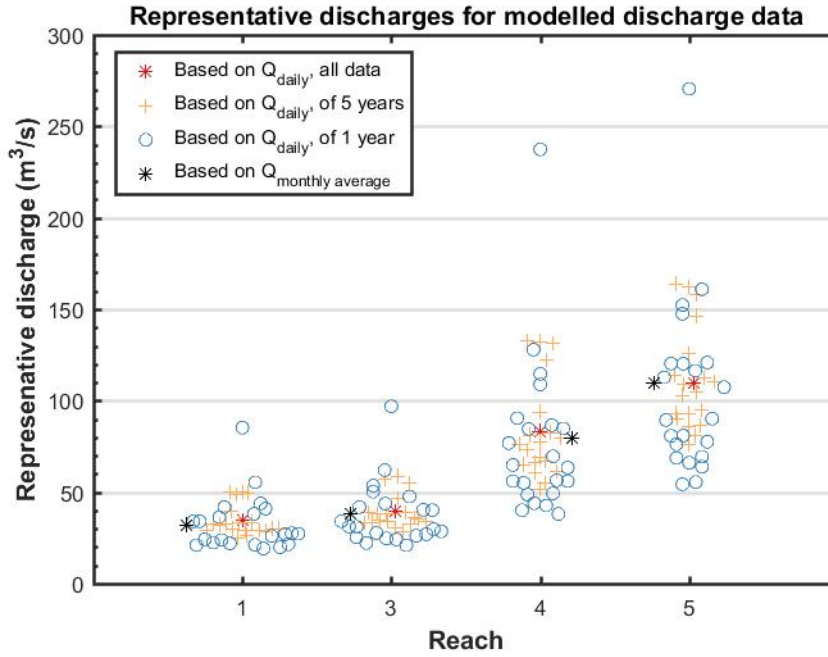


Figure A.6: Representative yearly discharges for records of Hulsman 2015. Representative discharge is calculated by Equation 2.15 for monthly average discharge and daily discharge.

A.2.2. Sediment transport capacity

- h_{max} is calculated with:

$$h = \left(\frac{Q * n_{max}^{3/5}}{B * i^{1/2}} \right) \quad (A.2)$$

- u is calculated:

$$u = \frac{Q}{(B * h_{max})} \quad (A.3)$$

- C is calculated with:

$$C = \frac{h_{max}^{1/6}}{n_{max}} \quad (A.4)$$

The resulting sediment flux for EH is calculated with:

$$Q_{s,EH} = i^{5/3} * Q^{5/3} * B^{-2/3} * C_{max}^{1/3} * \frac{0,05}{1,65^2 * D_{50} * 10^{-3} * \sqrt{9,81}} \quad (A.5)$$

The resulting flux for MPM is calculated with:

$$Q_{s,MPM} = 8 * (D_{50}/1000)^{3/2} * (mu * \Theta - 0,047)^{3/2} * (9,81 * 1,65)^{1/2} * 1000 \quad (A.6)$$

The results are given in the Figure A.7 and Figure A.8.

A.2.3. Equilibrium situation

The slopes calculated with the

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Figure A.7: Reference and EFA maintenance flows

	Q_EFA_2017_Floods																												
	Hydraulic parameters										Field parameter																		
Reach	Q	B	i	n	estima	hmax	f(nr href/hnew	u	uref/unew	C min	D50 (mm)	D90 (mm)	s EH max	s MPM max	Backcalculation														
0 Emarti - MKT	12,2	27	0,00135	0,0416	0,668888	1,863247817	0,675527	1,5141901	22,48014	0,3	20	0,006534708	0,12602611	0,000427259															
43	12,2	27	0,00135	0,0416	0,668888	1,863247817	0,675527	1,5141901	22,48014	0,3	20	0,006534708	0,12602611	0,000427259															
43 MKT-MKT	12,2	45	0,00508	0,0455	0,349089	3,570162751	0,776625	1,3170788	18,44214	0,23	1	0,05167428	0,16159171	0,002590276															
56	12,2	45	0,00508	0,0455	0,349089	3,570162751	0,776625	1,3170788	18,44214	0,23	1	0,05167428	0,16159171	0,002590276															
56 MKT-MPB	20	39	0,00094	0,0494	0,89182	1,397484766	0,575027	1,7788308	19,8603	0,4	0,9	0,004588347	0,04165404	0,0004															
128	20	39	0,00094	0,0494	0,89182	1,397484766	0,575027	1,7788308	19,8603	0,4	0,9	0,004588347	0,04165404	0,0004															
128 MPB-MM	31,26	60	0,00331	0,104	0,96466	1,291962444	0,540087	1,8939107	9,557897	0,4	0,9	0,046290214	0,11319016	0,004035459															
212	31,26	60	0,00331	0,104	0,96466	1,291962444	0,540087	1,8939107	9,557897	0,4	0,9	0,046290214	0,11319016	0,004035459															
	Q95																												
Reach	Q	B	i	n	estima	hmax	f(nr href/hnew	u	uref/unew	C min	D50 (mm)	D90 (mm)	s EH max	s MPM max	Backcalculation														
0 Emarti - MKT	2,1	27	0,00135	0,0416	0,232739	5,354944114	0,334185	3,0608118	18,85319	0,3	20	0,000328237	0,02254941	0,000625947															
43	2,1	27	0,00135	0,0416	0,232739	5,354944114	0,334185	3,0608118	18,85319	0,3	20	0,000328237	0,02254941	0,000625947															
43 MKT-MKT	2,1	45	0,00508	0,0455	0,121465	10,26059005	0,384198	2,6623674	15,46668	0,23	1	0,002595587	0,02783019	0,003794832															
56	2,1	45	0,00508	0,0455	0,121465	10,26059005	0,384198	2,6623674	15,46668	0,23	1	0,002595587	0,02783019	0,003794832															
56 MKT-MPB	2,75	39	0,00094	0,0494	0,271181	4,595845956	0,260022	3,9338116	16,28606	0,4	0,9	0,000157315	0,00298394	0,0004															
128	2,75	39	0,00094	0,0494	0,271181	4,595845956	0,260022	3,9338116	16,28606	0,4	0,9	0,000157315	0,00298394	0,0004															
128 MPB-MM	4,67	60	0,00331	0,104	0,308298	4,042529012	0,252461	4,0516165	7,903058	0,4	0,9	0,001827455	0,01361038	0,004646605															
212	4,67	60	0,00331	0,104	0,308298	4,042529012	0,252461	4,0516165	7,903058	0,4	0,9	0,001827455	0,01361038	0,004646605															

Figure A.8: EFA floods and Q95 flows

	Q_EFA_maint					Q_EFA_floods					Q_95				
	43	13	72	214		43	13	72	214		43	13	72	214	
Lreach (km)	43	13	72	214		43	13	72	214		43	13	72	214	
SI (-)	1,69	1,67	2,23	1,63		1,69	1,67	2,23	1,63		1,69	1,67	2,23	1,63	
L SI (km)	25,44	7,78	32,29	131,29		25,44	7,78	32,29	131,29		25,44	7,78	32,29	131,29	
i0 (m/m)	0,00135	0,00508	0,00094	0,00331		0,00135	0,00508	0,00094	0,00331		0,00135	0,00508	0,00094	0,00331	
Q0 (m3/s)	34,42	34,42	39,90	83,10		34,42	34,42	39,90	83,10		34,42	34,42	39,90	83,10	
QEFA (m3/s)	6,90	6,90	8,00	8,96		12,20	12,20	20,00	31,26		2,10	2,10	2,75	4,67	
dQ (m3/s)	27,52	27,52	31,90	74,14		22,22	22,22	19,90	51,84		32,32	32,32	37,15	78,43	
i1 (m/m)	0,00673	0,02534	0,00469	0,03070		0,00381	0,01433	0,00188	0,00880		0,02213	0,08326	0,01364	0,05890	
Change in slope (i0/i1)	4,99	4,99	4,99	9,27		2,82	2,82	2,00	2,66		16,39	16,39	14,51	17,79	
delta z (m)	231,53	263,39	269,87	5861,20		105,73	120,28	67,34	1174,68		893,42	1016,39	914,30	11896,17	
Delta z SI (m)	113,30	131,23	83,69	3322,05		38,86	45,53	-7,13	446,88		504,95	582,12	372,67	7024,49	
h (m)	0,48	0,25	0,51	0,46		0,67	0,35	0,89	0,96		0,23	0,12	0,27	0,31	
L (m)	1066,67	147,64	1627,66	416,92		1488,89	206,69	2840,43	870,09		511,11	70,87	861,70	280,97	
Qs (m3/s)	0,01363	0,01363	0,01363	0,01363		0,01363	0,01363	0,01363	0,01363		0,01363	0,01363	0,01363	0,01363	
B (m)	27	45	39	60		27	45	39	60		27	45	39	60	
Timescale (seconds)	2966810712	1860664710	2983903448	16164845194		2966810712	1860664710	2983903448	16164845194		2966810712	1860664710	2983903448	16164845194	
Timescale (years)	941	5900	946	5126		941	5900	946	5126		941	5900	946	5126	

Figure A.9: Reference and EFA maintenance flows

B

Numerical calculations

General method: The steps undertaken are as follows:

1. A model is set up, forced by the representative discharge, and other parameters as calculated during the analytical analysis. The model is then calibrated for a constant sediment transport flux, resulting in very small bed level changes. D_{50} and bed level steps between transitions of reaches are calibrated to this use. This is needed because the Sobek-RE model uses different method to calculate the hydraulic parameters velocity and depth compared with the calculations in section A.
2. With the new model parameters for D_{50} , topography (the slope stays the same), and sediment transport, the model is forced with the monthly average discharge regime of the historical data. The results for this forcing form the reference scenario.

First, the bed load - discharge relationship for upstream needs to be calculated by the model. The resulting incoming sediment flux is in this way made dependent on the discharge.

Secondly the model is forced with the monthly average discharge regime.

3. With the same model parameters as in 2, the model is forced with the proposed discharge by the EFR.

B.1. Set up of the morphodynamic model

In order to model the river, it needs to be simplified to an extend that one dimensional processes in longitudinal direction can be calculated, that are representative for the river. For this schematisation, the Mara River is divided into 5 reaches, see Table B.1. Sediment transport theory and formulas are used to calculate sediment transport and bed level changes. The Sobek-RE model is a numerical model used for scenario modelling. The model couples the 1D Sain Vennant hydraulic equations with the sediment transport formulas, solving the equations iteratively (adapting bed level, water depth and discharge). It assumes capacity limited transport. Since the model is one dimensional, only changes along the longitudinal axis of the river will be modelled. In the longitudinal direction, sections are made based on characteristics like slope, width and sinuosity, see Figure B.1. The cross sections are simplified to a rectangular cross section where only the width needs to be defined, there the rivers cross sections will be very variable with all the pools and riffle sections. Initial elevation of the reaches is determined from the NASA STRM3 data (see section 3).

B.1.1. Boundary conditions

A numerical model always needs boundary conditions for solving the equations. Two boundary conditions are needed to solve the hydrodynamic equations, an upstream and a downstream boundary since the flow in the river is generally sub critical. And since the sediment module only needs information from one boundary, the flux of sediment will be stated at the upstream boundary. Also the geometry is seen as a spatial boundary of the system.

Discharge The incoming discharge at Emarti is simplified as the sum of Amala and Nyangores gauging stations, since these stations have a long time series. Additional discharge flows in at points are chosen to be at the boundary of reaches. The yearly average and monthly average discharge are used to construct the reference scenario.

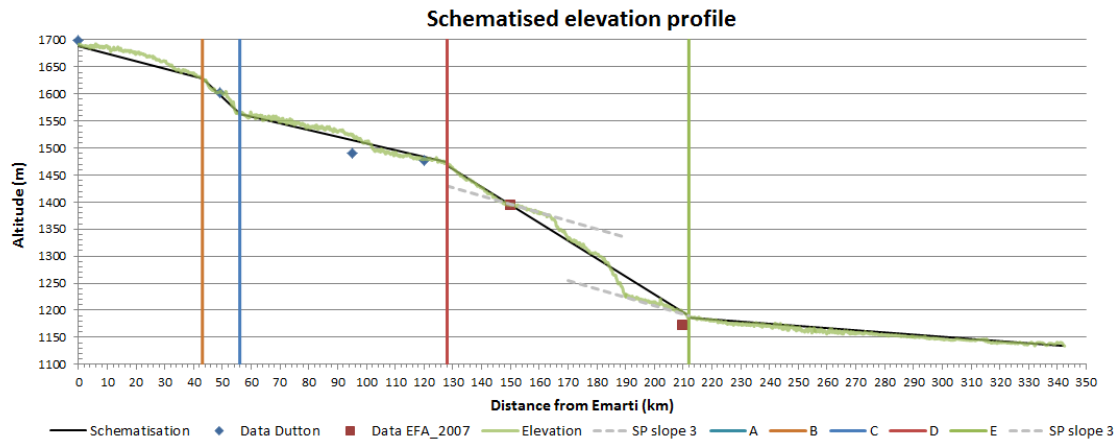


Figure B.1: Schematised elevation when the river is divided into 5 reaches

Table B.1: Schematisation of the river in 5 reaches with length, slope, width, and sinuosity index (SI)

Reach	Length (km)	Width (m)	Slope (m/m)	Sinuosity (-)
Emarti - Kichwa Tempo	43	27	0.00135	1.69
Around Kichwa Tempo	13	45	0.00508	1.67
Kichwa Tempo - Purungat	72	39	0.00094	2.23
Purungat - Mines	84	60	0.00331	1.63
Mines - Lake Victoria	130	44	0.00035	1.87

- Reach 1; Emarti - Kichwa Tempo – Nyangores + Amala
- Reach 2; Around Kichwa Tempo – Nyangores + Amala
- Reach 3; Kichwa Tempo - Purungat Bridge – Nyangores + Amala + half of Middle Mara as defined by Hulsman.
- Reach 3; Middle of the reach; Nyangores + Amala + 0.5 Middle Mara + Lemek + Talek
- Reach 4; Purungat Bridge - Mara Mines – Nyangores + Amala + Middle Mara + Lemek + Talek + Sand
- Reach 5; Mara Mines - Lake Victoria – Nyangores + Amala + Middle Mara + Lemek + Talek + Sand + Lower catchment

Downstream water level The river flow out into Lake Victoria, which could be a perfect downstream boundary. However, several reasons prompted to not investigate further into the Lake Victoria water levels. Firstly, there is limited knowledge about the geometry of the wetland, flow variables there. Secondly, from Google Earth, it can be seen that the river splits up a some 30 kilometres after Mines. Moreover, due to the lack of knowledge about the geometry, the lake levels would be difficult to relate to the river conditions. And lastly, it can be expected that the wetland/swamp is under influence of the backwater curve expected from Lake Victoria. (Mtamba et al. 2015, Mturi 2007). For this research, the water level at Lake Victoria is taken as a constant value, what means that the area under influence of the back water curve, the wetland, will not be within the area of interest for this study.

Morphological boundary condition As there is no data on bed load sediment fluxes, for the reference model the assumption is stated that the river is in equilibrium and that the transport rate is equal to the transport capacity of the river based on slope, discharge and geometry. In this way, the sediment flux can be calculated as outcome of the calculation. For the reference scenarios, the same sediment flux is taken as upstream morphological boundary condition. The downstream boundary condition is $s = 0 \text{ m}^3/\text{s}$, in order to close the sediment balance.

B.1.2. Assumptions

Due to constraints within the available data and model, assumptions have to be taken, which are discussed after analysing the results. The assumptions are:

1. *Simplification in elevation profile.* No bed level jumps are taken into account, however, from field visit it is clear that the river contains a lot of pool-riffle and step-pool features.
2. *Alluvial character of the river.* The sediment transport modelled by Engelund Hanssen is assumed to be purely alluvial, where it always can be picked up and eroded. Moreover, the sediment sizes that Engelund Hanssen validated their formula for are $0.0009 \text{ m} < D_{50} < 0.021 \text{ m}$. Thirdly, the alluvial river character suggests a capacity limited river. There the Mara is also governed by bedrock parts, this will not be valid everywhere.
3. *Straight channel.* The one dimensional model only calculates velocity, bed level changes in longitudinal direction, assuming that the parameters are constant throughout the cross section. This implies that cross sections are symmetrical, and there are no variations in lateral direction. Also bank erosion can not be taken into account there this is a process that acts in lateral direction.
4. *Discharge simplified to monthly average discharge.* There a monthly average discharge is taken as boundary condition, peaks in the discharge as flood pulses will not be taken into account. Sediment transport is highly dependent of discharge, calculating sediment transport with Engelund Hanssen formula the discharge is even to the power 5 related with the sediment transport, however, for long term geomorphological calculations, these short term flood pulses can be considered as negligible (Crosato and Paron, 2014). For short term, the function of these pulses are very important, there they flush the fine sediments from the river bed, creating open space which is good habitat for fish.
5. *Reaches have constant width and discharge.* Each reach is assumed to have constant width and within a reach the discharge will not change. At the transition of the one reach to the next reach, the width and discharge change on the last grid cell of the reach.

B.1.3. Scenario modelling

Little data availability on the morphology of the river (bed load sediment, bed elevation over years), restrict the modelling exercise to only assess differences of sediment transport compared with a reference scenario that represents the current state. This reference scenario is based on the assumption that the river bed is currently not eroding or aggregating, implying that the sediment transport is spatially constant. The parameters as grain size and roughness will be found by modelling this reference scenario, after which adaptations for the future are modelled.

B.1.4. Reference scenario

As said above, the reference scenario is the scenario which represents a stable bed of the river. Assuming also that the river is purely alluvial, Engelund Hanssen is applied as sediment transport formula. The sediment flux generated by the river in equilibrium is calculated with the data that is available through data acquisition. Consequences of this method is that the dynamics of the river will be based on the sediment transport of one reach, there sediment transport flux will be chosen to be the constant flux along the river.

B.2. Results

For the reference scenario, first a constant discharge is applied as forcing on the model, and the results will be calibrated on D_{50} and C , with the objective to minimize bed level changes. The second step is to apply the monthly average discharge regime as upstream boundary/forcing. Results of both runs will be given in this section.

B.2.1. Constant discharge

The hydraulic results from the model simulation for a constant discharge are within the range of the manual calculations, which is a verification of the results from the model, which can be seen in Figure B.2. The discharge increases in volume along the length of the river. From $25 \text{ m}^3/\text{s}$ for Emarti - Kichwa Tempo, $34 \text{ m}^3/\text{s}$ for Massai Mara, $43 \text{ m}^3/\text{s}$ for Serengeti park to $55 \text{ m}^3/\text{s}$ in the floodplain reach.

Sediment simulation of the Sobek model are slightly higher than the manual calculations, see Figure B.3. The flux of sediment at the upstream boundary is adjusted to the simulated sediment flux in Sobek. Differences after 1 and 500 years are minimal (Figure B.3 right plane.)

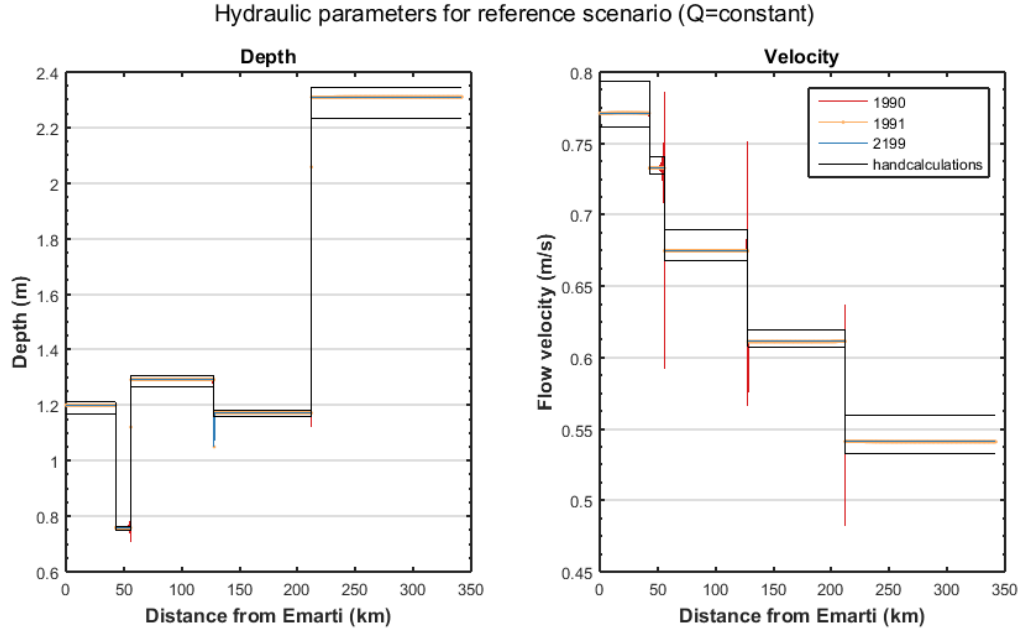


Figure B.2: Depth and velocity results of the model simulation for constant discharge and manual calculations.

The simulated bed level steps at the transition of reaches differ with the manual calculations by 0.4-0.5 m. These differences are as well adjusted for in the input of the model, by adjusting the bed levels of cross sections. The resulting bed level change over the longitudinal direction of the river results in a maximum erosion of 17.5 cm at Emarti after 500 years, decreasing when moving downstream, (Figure B.4). This is considered an acceptable rate of erosion for the static reference scenario. The calibration parameters; D_{50} and C are based on this scenario are summarized in table B.2.

Around the changes of slope, at the boundaries of reaches, big variations in velocity, depth and thus in sediment transport can be seen. This results in responses of the bed level. These large variations are seen as artefacts, because in reality, the transition of reaches goes smoothly. In the model big variation exist because of the big change in slope, water depth, velocity and thus sediment transport and bed level. Overlooking the whole profile, the sediment transport stays quite stable, and so should the bed level. The continued erosion show signs that the profile is not yet fully in equilibrium. However, the amount of erosion is so small that it is considered to be negligible.

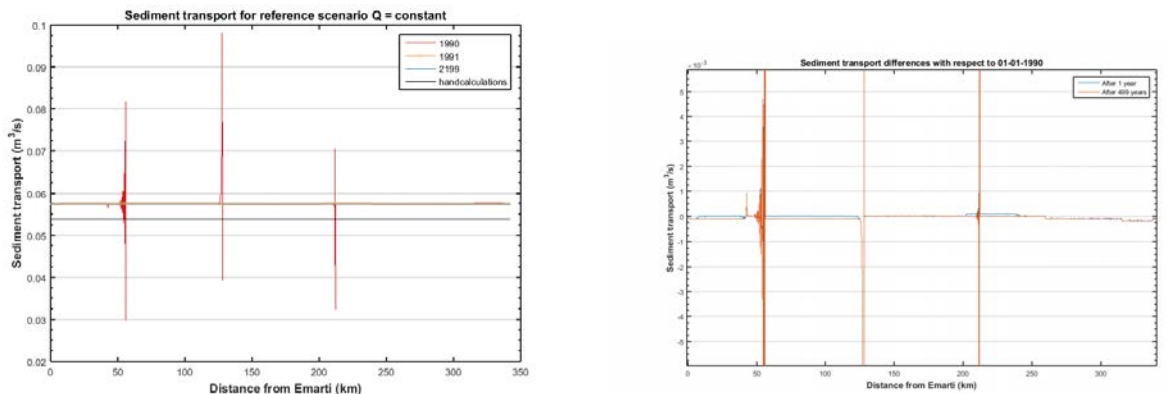


Figure B.3: Left: Sediment transport as result of the model simulation and manual calculation. Right: Differences in sediment transport after 1 and 500 years.

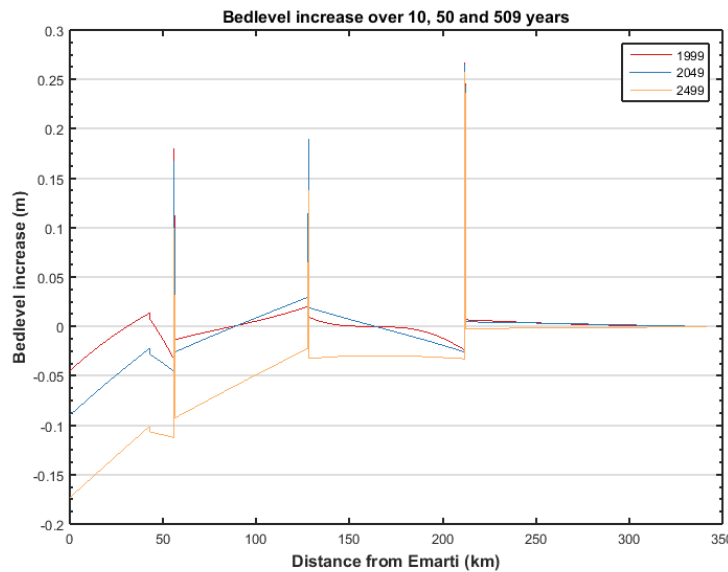


Figure B.4: Bed level changes after long term model simulation for calibration of the reference scenario.

Reach	Slope (-)	Chezy roughness ($m^{1/2}/s$)	Manning roughness ($s/m^{1/3}$)	D_{50} (m)
1. Emarti - Kichwa Tempo	0.00135	20	0.050597	0.000162
2. Around Kichwa Tempo	0.00508	12	0.079	0.0000967
3. Kichwa Tempo - Purungat	0.00094	20	0.05145	0.0001199
4. Purungat - Mara Mines	0.00331	10	0.101826	0.0009
5. Mines - Lake Victoria	0.00035	20	0.056256	0.0000448

Table B.2: Variables calibrated on stable reference scenario

B.2.2. Monthly average discharge regime

Roughness of the channel The Manning coefficient for the Mara river should be minimum $0.03s/m^{1/3}$, for gravel-few boulder parts, and maximum $0.07s/m^{1/3}$, for substrate containing cobble and large boulder parts (Chrow, 1959). In appendix ?? images give a good view on the bed material at Emarti and Kichwa Tempo. In this view, the coefficients for Kichwa Tempo and Serengeti park are quite high. But the steep slope, large variation in width, sinuosity, big boulders as substrate together with the evidence from Google Earth that there are many pool-riffles sections, support these values. Van der Waal performed a hydraulic analysis for Purungat and Mara Mines with the data obtained in the 2015-2016 field survey (Van der Waal 2016). He calculated roughness values of $0.052s/m^{1/3}$ at Purungat bridge and $0.042s/m^{1/3}$ at Mines. Taking everything together, it is recognized that the river is highly heterogeneous, which will not be covered by the Sobek model. It is however not the purpose of this research to simulate the details of the heterogeneous river, but to simulate sediment transport along the whole main stem. This means that simplifications need to be made. It is well possible that in reality the average value of the roughness per reach is lower, but here the roughness is based on the field measurements with the underlying motivation that the locations of these measurements are representative for the reach.

Hydraulic analysis The velocity for each reach is compared with field measurements that have been done in that reach, to check if the order of magnitude is good. Comparing the values in table B.3, the model passed this validation.

Sediment transport Sediment transport rates vary as flow velocity varies over time. The results of monthly sediment transport rates for the first year can be seen in Figure B.6, where they are also compared with the

Table B.3: Hydraulic results from Sobek model compared with field measurements * = data obtained from literature (Ndomba, P.M. and Mtamba 2012 and Muthike et al. 2007b) ** = surface velocity; measured by floats (*0.7 = 2.01 m/s). Only high discharges are displayed, there the low discharges are not modelled because of the monthly average input of discharge.

Site	$Q_{measured}$ (m^3/s)	$u_{measured}$ (m/s)	Q_{model} (m^3/s)	u_{model} (m/s)
Mara Beef December	47.535	1.141	47.21	0.98-0.99
Emarti Bridge October	22.241	0.927	22.3	0.74-0.75
Safari Club* July	16.624	0.865	16.59	0.66-0.67
Mara Kichwa Tempo September	14.766	0.460	14.75	0.59-0.61
Serena Pumphouse September	13.006	0.419	15.37	0.50-0.54
Purungat Bridge December	75.104	1.267	59.67	0.84- 0.91
Kogatende* May	117.98	1.02	116.9	0.87-0.90
Mara Mines* May	529.32	2.13	180.9	0.81-0.84

transport rate of the constant discharge reference scenario (CDRS). It can be seen that sediment transport rates for March-April-May (the long rains), is higher than the CDRS. The sediment fluxes for the months July-August-September stay below the sediment transport flux of the CDRS. These are also the months where the sediment transport is most stable, and thus few changes in bed level can be expected. For all other months, an increase in transport rate over the length of the river is found, which means erosion will take place. The months March-April-May have the most increase in sediment rate, and are the most erosive months. This is explained by the long rains during this time, when discharge is highest and thus stream power of the river is big.

In Figure B.7 the monthly sediment fluxes are standardized by dividing the monthly flux by the yearly average. From this figure it is more clear that the months July-August-September have declining standardized sediment transport rates over the length of the river. Also the months March-April-May have by far the highest standardized transport rates, and thus are the months where the most erosion is expected.

The temporal change of this monthly sediment transport variation is plotted in Figure B.8. The sediment transport is getting more constant over the length of the river, which means that it is thriving towards an equilibrium. Also, sediment transport rates are in general declining over the years.

Bed level change Bed level changes with respect to $t=0$ can be seen in Figure B.9. The erosion peak can be seen around 130 km from Emarti, at the same location as where the sediment transport has a high jump in Figure B.6. This is the transition at Purungat Bridge where slope changes significantly from 0.00094 to 0.00331 m/m . In the floodplain reach, the erosion gets much less, there this section deposits during most months (see Figure B.7).

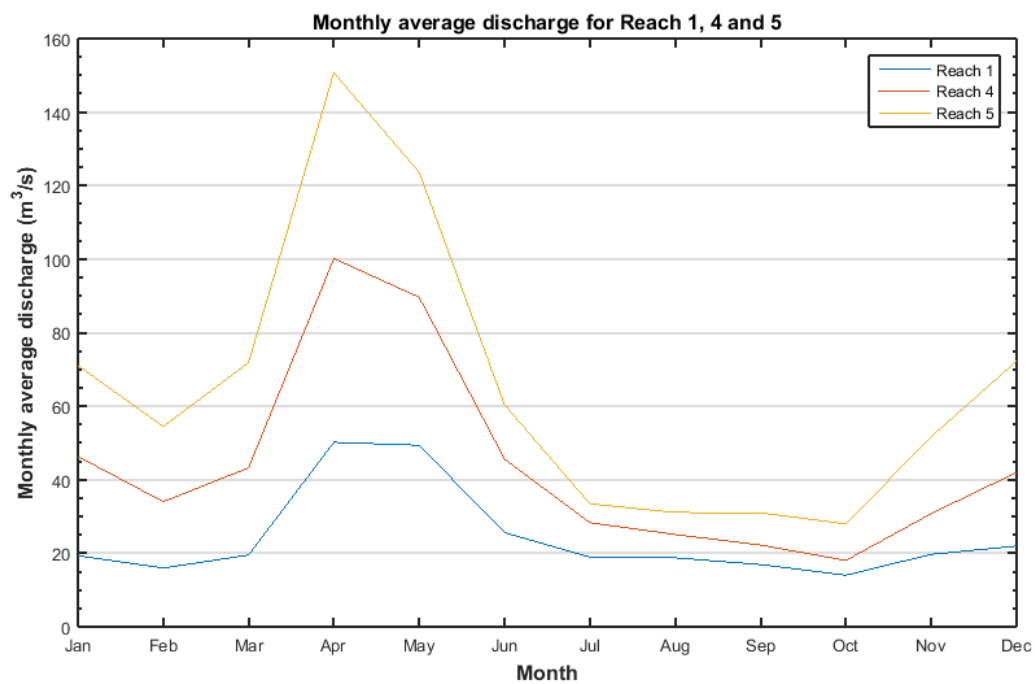


Figure B.5: Monthly average discharge for Reach 1, 3 and 5

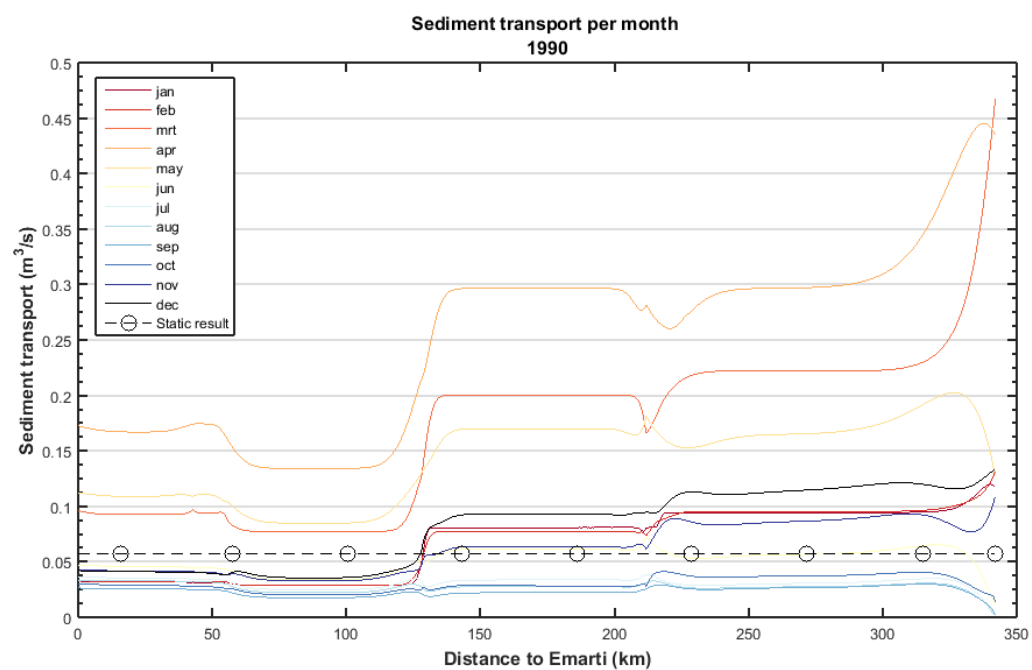


Figure B.6: Sediment transport over length of the river for all months in 1990

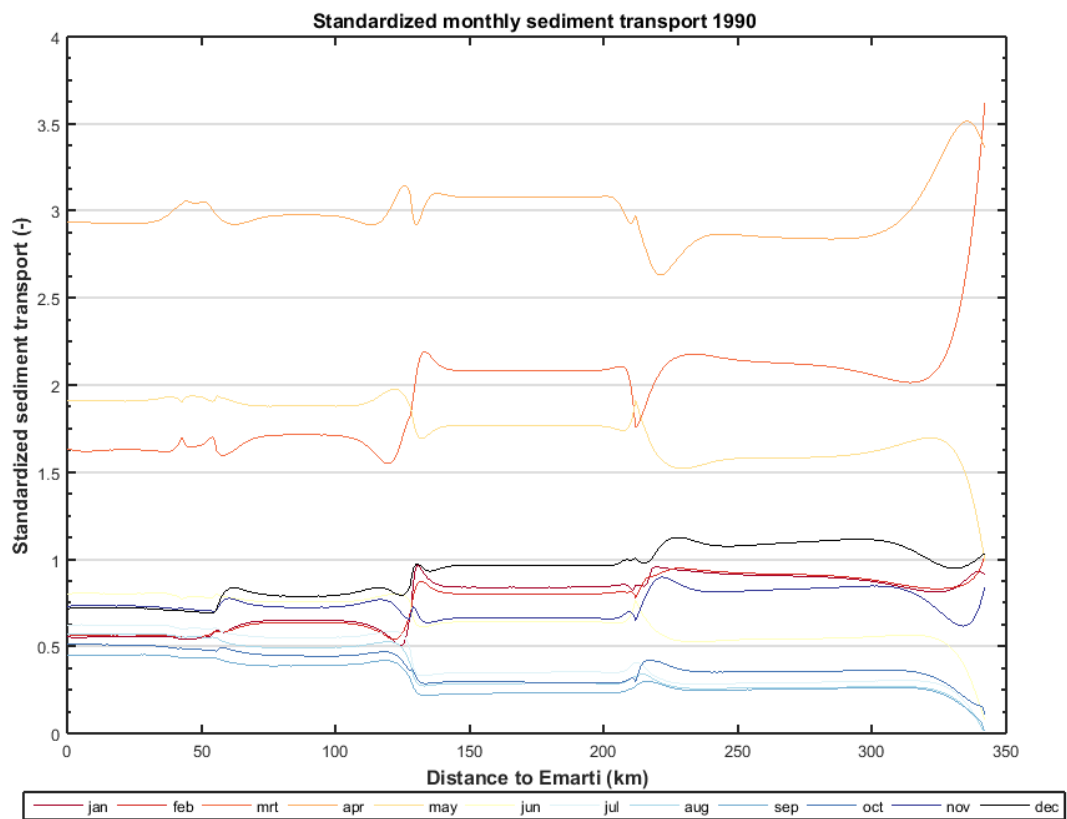
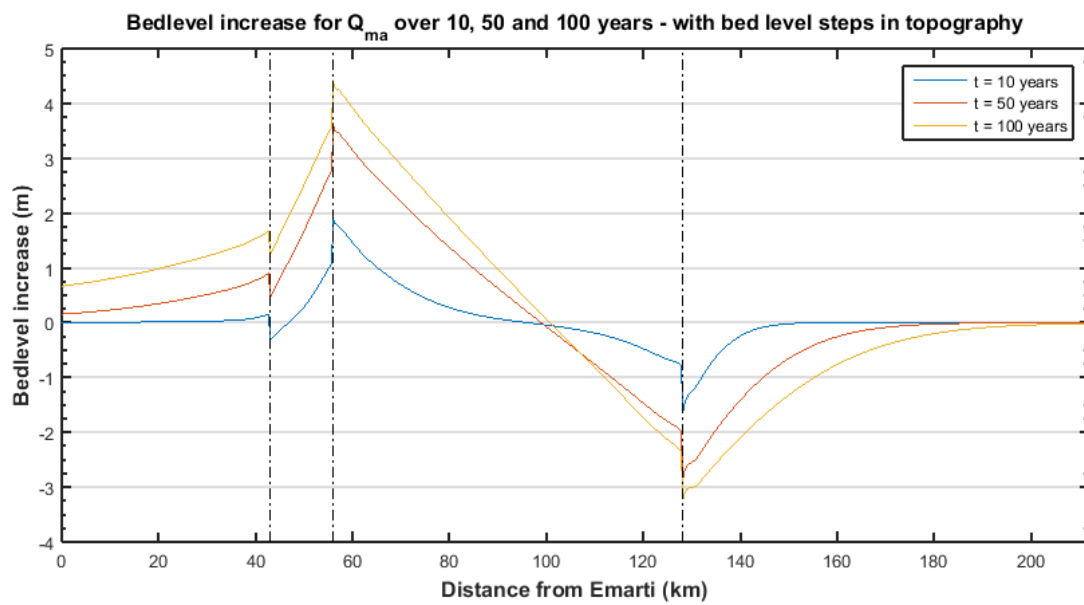
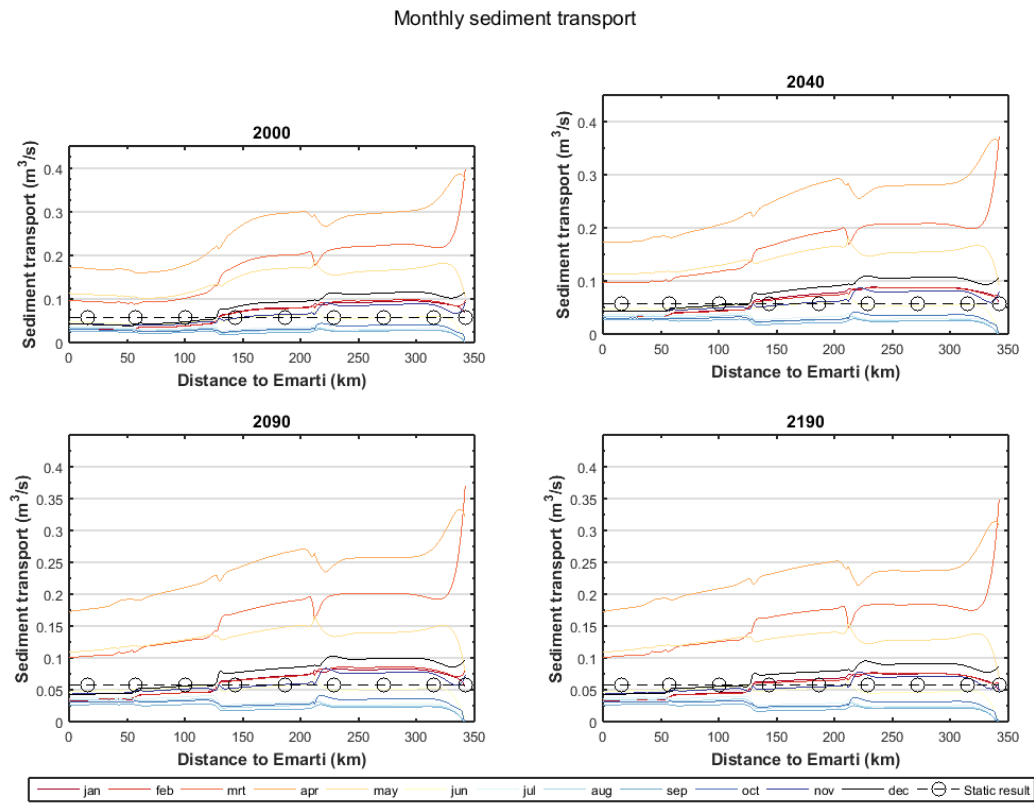
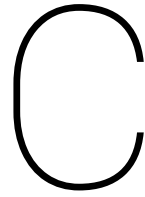


Figure B.7: Monthly sediment transport for reference scenario with a variable discharge





Technical report of the Field surveys

During the field survey the geometry of the river, an assessment of the current morphology, and relationships between discharge and stage height is acquired. The trip consisted of different parts. First, together with the EFA- team a high flow survey at 7 selected EFA sites along the main Mara and its tributaries, including one site in Tanzania, Mara Mines site, wa. After that, monthly monitoring surveys together with WRMA officials provided insight in 3 additional locations on the river. And at last, an EFA low flow survey was taking place, where the sites in Kenya were surveyed again, together with a visited an oxbow lake in the meandering part of the river. The EFA sites were selected according to previous EFA surveys, when the sites were selected on how representative the site is for a specific reach. Monthly monitoring sites are selected on where gauging stations are located. At the border an additional discharge is measured monthly, but here there is no gauging station, since this location lies within the Massai Mara, and it is difficult to have a gauge observer.

The hydraulic and geomorphologic surveys were focussed to measure specific transects along the site. These transects were chosen based on the applicability for the vegetation, hydraulic, macro invertebrate and fish survey. Often at least a pool and a riffle section were chosen. The hydraulic survey consisted of measuring the discharge with the River Surveyor, which is a small unmanned boat, with an acoustic Doppler and DGPS on the boat to measure position, depth and flow velocity. The results are thus discharge, maximum, minimum velocities, wet cross section and width of the river. For the geomorphologic survey the dry cross section was measured starting from the furthest reachable point in the water (water edge when hippos were present, otherwise a few meters in the water could be measured) and ending with the highest visible point on the cross section. This was done during high flows with a total station, which measures the distances and angles to a point in the cross section with respect to reference point by sending out a laser beam. During low flows a DGPS was used, which gives the exact position of the device in latitude, longitude and height with respect to the geoïd. In the cross section, annotations about the bed and bank material were made. Also samples along a stretch of 50 m were taken from the banks, flood deposits and where possible bed material were taken and analysed. Sediments smaller than fine gravel were taken to the lab for a grain size analysis. Sediments bigger than gravel were measured in samples of 100 pieces with a ruler or calliper at the site. Also pool, riffle, rapids were identified, and a general description of the site was made. Where possible, grab samples were taken from bridges with a grab sampler “Van Veen”. During the December monthly monitoring this equipment was also present, unfortunately during the January monitoring round this was not the case. This report discusses the results of the survey per site per surveys that were undertaken. For each site the results will be presented, which are cross section measurement, discharge measurement, grain size analysis and a general site assessment on characteristics of geomorphology, hydraulics, vegetation and fish.

Table C.1: Overview of sites visited and measurements taken. * Only measurement of water level slope

Date	Site	# Transects; Total Station	River Surveyor	Flow Tracker	# Suspended Sediment	# Sediment Samples
<i>EFA high flow survey</i>						
27/11/2015		1	1	0	1	7
28/11/2015	Mara Mines					
30/11/2015	Purungat Bridge down bridge	7	7	0	1	4
01/12/2015	Purungat Bridge up bridge	2	2		2	4
02/12/2015	Sand	3	0	3	3	6
03/12/2015	Talek Olare Orok	2	1	1	2	5
05/12/2015	Mara Beef	2	2	0	1	4
06/12/2015	Nyangores Silibwet	3	4	0	1	3
07/12/2015	Nyangores Chemomul	1	4	0	3	5
08/12/2015		3	4	0	2	4
09/12/2015	Amala Kapkimolwa					
<i>WRMA monthly monitoring survey</i>						
15/12/2015	Mara Kichwa Tempo	1	1	0	1	4
16/12/2015	Emarti Bridge*	Wsl	0	0	1	1
17/12/2015	Nyangores Bomet	1	1	0	2	2
07/01/2016	Talek RG/Gate	0	0	1	1	3
08/01/2016	Sand RG/Gate	0	0	0	1	4
08/01/2016	Purungat Bridge	0	1	0	1	2
09/01/2016	Mara Kichwa Tempo	0	1	0	1	3
09/01/2016	Mara Emarti Bridge	0	1	0	1	2
10/01/2016	Amala Kapkimolwa	0	1	0	1	2
10/01/2016	Nyangores Silibwet	0	1	0	2	3
10/01/2016	Nyangores Bomet	0	1	0	1	2
27/01/2016	Talek RG/Gate	1	1	0	0	0
27/01/2016	Mara Emarti Bridge	1	0	0	0	0
<i>EFA low flow survey</i>						
29/02/2016	Purungat Bridge up Bridge	2	2	0	1?	2
01/03/2016	Purungat Bridge down Bridge	5	5+	0	0	3
02/03/2016	Sand River	-	-	-	-	1
03/03/2016	Talek Olare Orok	3+4	2	1+4	1?	4
04/03/2016	Oxbow lake	-	-	-	-	-
05/03/2016	Emarti/Mara Beef	2	3	0	1?	3
06/03/2016	Nyangores Chemomul	1	3?	0	1	1
07/03/2016	Nyangores Silibwet	3	3	3	1	2
08/03/2016	Amala Kapkimolwa	3	3	0	1	3
09/03/2016	Amala Kapkimolwa (DGPS)					

C.1. Mara Mines

27/11/2015 - 28/11/2015

Mara Mines was the first site visited with the EFA team, on 27-11-2015 and 28-11-2015. This site is just upstream of the wetland area, after which the river flows into Lake Victoria. Along the river the land is used for agriculture and some settlements have been seen. Cattle as goats and cows are grazing in the area. During the visit, there was a very high flow in the river, even saw a zebra was floating by. Under these circumstances it was only possible to survey one cross section, right where the gauging plate is located. A little upstream there was a rock outcrop where the water created a riffle, where the flow was very rough. At the surveying transect the water was flowing more quietly. Due to the high discharge and wide channel, the discharge measurements, the boat was not able to cross the river within the range of the Blue-tooth mobile receiver. Therefore, also float measurements with wood debris were done on 27-11-2015. The fish and macro invertebrate survey were done a little upstream of the gauging station, in the shores of the riffle section.

C.1.1. Habitat mapping

In Figure C.3 the sketch of the plan view of the habitat can be found. At the place of the transect, the flow was quite laminar at the surface. At the right hand bank, an eddy was created by a shrub in the water, and flow here was slower. The banks along this eddy were slumping, creating the steep edge, see Figure C.2. Furthermore, the banks were vegetated with grass, and from this fieldwork, the cross section could not be assessed better. At the riffle section, the flow was very rough, and trees were inundated. The habitats found were: high flow, deep in the main part of the river. In the eddy, there was deep, slow flow over sand. In the riffle there were a lot of waves, shrub inundated, and along the water edge there were waves as well. Bed material was probably bedrock, vegetated and sand along the sides, this is based on pictures of previous EFA were found, see Figure C.1.



Figure C.1: Impression of Mara Mines site from previous EFA survey. From left to right: Site overview looking downstream, Riffle section bed material (grass, boulders), Cross section of site



Figure C.2: Impression of Mara Mines site 27-11-2015. Left: Slumping right hand bank, at location of eddy. Right: Riffle just upstream of gauging station

C.1.2. Discharge

The discharge was only measured the 28th, because the first day was mainly a reconnaissance day. The second day the water level was even higher, which made it difficult to use the River Surveyor. The maximum velocities measured with the River Surveyor were 3 m/s. The mean velocity of the best run of the River Surveyor was 1.5 m/s, these measurements were done over a width of 50 meter, and the total discharge for this run was $251 \text{ m}^3/\text{s}$. Extrapolating to the total width of the channel (65 m), the discharge would be $251 \times 1.3 = 326.3 \text{ m}^3/\text{s}$. The floating method gave us a water velocity of ranging from 3.4 – 1.85 m/s, the average of 20 measurements was 2.6 m/s. This gives us together with the width measurement of the Total station of 65 m

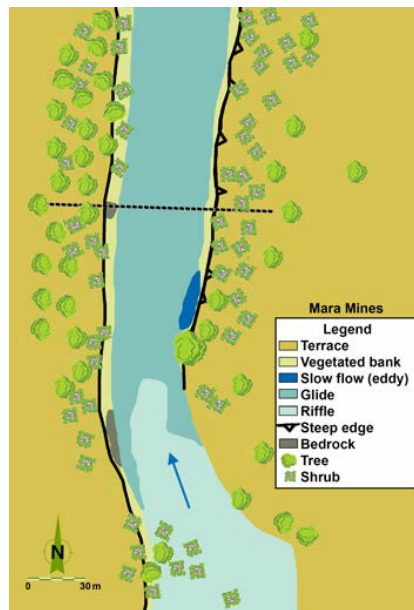


Figure C.3: Plan view of the habitat seen at Mara Mines 27-11-2015

Table C.2: Discharge measurements and corresponding gauge height. *Floating method **RiverSurveyor extrapolation.

Discharge (m^3/s)	Gauge height (m)	Time and day
676.8*	3.64	11.00am 27/11/2015
	3.68	3.20 am 27/11/2015
	4.95	11.00am 28/11/2015
	4.95	11.00 am 28/11/2015
326.3		

and a depth of the River Surveyor of 4.45m gives us a discharge of $65 \times 4.45 \times 2.6 \times 0.9 = 676.8 \text{ m}^3/s$. The water level slope was measured over a distance of 304 m, at the left hand bank. The slope was 0.000972 m/m.

C.1.3. Cross sectional profile

Made with TS and RiverSurveyor data points; all points from the River Surveyor are used. Since this site was only visited during the high flow season, this is the cross section we are constricted to. The cross section complies with the cross section measured by Ndomba in the previous EFA study (Ndomba, P.M. and Mtamba 2012).



Figure C.4: Cross section Mara Mines measured during high flow with the Total Station

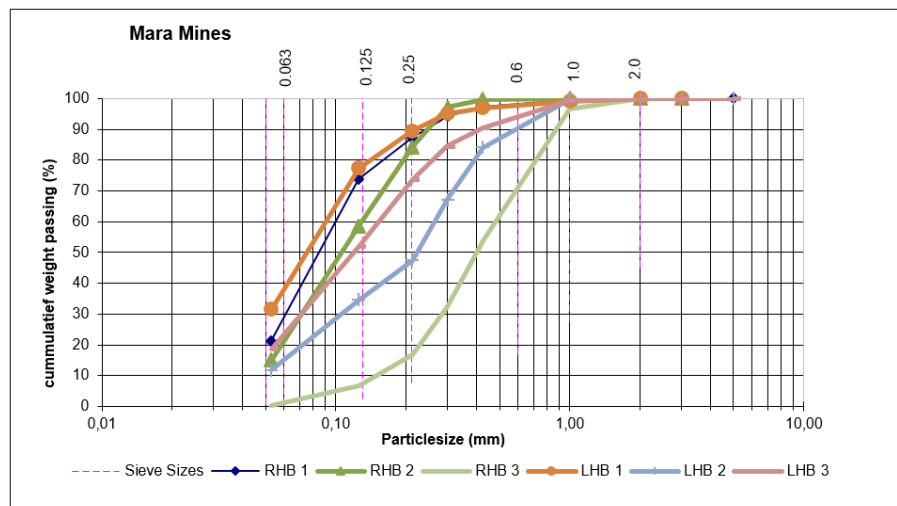


Figure C.5: Sediment distribution for Mara Mines. Description of the samples is given in Table C.3.

Table C.3: Sediment samples and classification. RHB meaning Right hand bank sample and LHB meaning Left hand bank sample.

Sample	D_{50}	Remarks
RHB 1	0.0849	Flood plain
RHB 2	0.105	Bank material (slumping bank)
RHB 3	0.400	In channel, eddy 3.5m deep
LHB 1	0.0749	10cm below water level
LHB 2	0.222	15 m from water edge (just before flat land)
LHB 3	0.119	40m from water edge, flat land

C.1.4. Sediment analysis

Sediment samples were collected along the river, and the floodplain. The flow was too high to get good bed sediment samples. We only managed to get a grab sample at an eddy at the right hand bank. The water depth was about 3.5 meters for this eddy.

Suspended sediment The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature.

Table C.4: Suspended sediment samples; turbidity, load of suspended sediments and discharge at the sampling time. NTU = Nephelometric Turbidity Unit

Q (m^3/s)	Turbidity (NTU)	SS (mg/L)	Source
676.6	994	2850,1235	Field measurement
529.32	581	118	EFA measurement May 2012
238.8	714	122.5	EFA measurement May 2012
2.5	27.6	30	EFA measurement Feb 2012

C.2. Purungat Bridge

30/11/2015 - 01/12/2015 - 08/01/2016 - 29/02/2016 - 01/03/2016

At Purungat bridge, located near the border of Tanzania and Kenya, two sub sites were assessed for the EFA field survey (High flow: 30/11/2015, 01/12/2015, Low flow: 29/02/2016 and 01/03/2016). First one in the pool area just upstream of the bridge, and the other sub site below the bridge, where riffle flow was present at the low flow survey. The monthly monitoring site (08/01/2016) is usually downstream of the Purungat bridge; at the most suitable location taking into account wildlife and eddies. During the EFA survey, 7 transects were chosen downstream, to include the variability of the pool-riffle morphology there. In the pool section 2 transects were measured. During high flows, also some tributaries of the river were visited for the macro invertebrate and fish survey.



Figure C.6: Overview of the site at Purungat bridge from Google Earth

C.2.1. Habitat Mapping

Pool section The site is heavily incised, about 5 m, while the left hand bank is also 1.5 m undercut. The in-stream sand benches along the left hand bank during low flow are consolidated, and difficult erodible. While the left hand bank show signs of recent collapsing, the right hand bank is more stable. Also bedrock is located here along the hill slope, and the slope is more gentle and vegetated than the left hand bank. Upstream of the site (250 m), the river has made a 90 degrees bend, and just downstream of the site (75m) the river is bending in the same angle again. But difference here is that just before the bend, already bedrock is visible during low flow, and the riffle starts. Just before the riffle another hippo pool was located during the low flow. During high flow the flow was quite uniform accross the width, and a plain bed flow. No pools were found along the sides. During low flow, there was a stagnant water zone identified along the left hand bank. And a lee bar was found at the downstream side of this stagnant water zone, where the remenants of a tree created this lee bar. The distance between banks is approximately 50 m.

Riffle section The slopes of the river at the riffle section are more gentle and more vegetated. This part is bedrock controlled, and vegetated sand benches are found along the hillslopes. The bed consists of bedrock, bedrock outcrops and boulders. The incision is at the same scale as the pool section (6 m), but the banks are much more gentle, providing a wider range of habitats. Bedrock at the channel bed, but gravel and sand pockets were found between the rock outcrop found. Downstream and downstream of the rock outcrop on the right hand bank, a pool section with slow-stagnant flow is found. On the right hand bank also signs of a secondary flow are found, which would go around the rock outcrop on this side of the channel. During the high flow season, the velocities here were also lower than in the rest of the cross section. A few hippo pathways are found from the water to the terrace, connecting the banks with the river. The hillslope on the right

hand bank is heavily vegetated with high grasses and shrub. The distance between the terraces is therefore a little wider; ± 60 m.

Velocity/Depth plots The difference between the two sites can also be seen well in the velocity-depth graph. The low flow plot shows that the habitat in the pool section is confined to shallow and deep-slow parts, which complies with the fact that there was only stagnant water, and laminar slow flow. In the riffle section however, the velocities are much more divers, as the velocity-depht ratio. For the high flow plot, the velocities and depths for the pool section are again concentrated around 1 m/s and 2-2.5 m depth. The riffle section shows one, evenly devided cloud across the range of velocities and depths that were measured.



Figure C.7: Pictures taken at Purungat Bridge. Left: Purungat Pool looking upstream; Middle: Purungat riffle, taken from bridge during high flow; Right: Purungat riffle, taken from bridge during low flow.

C.2.2. Discharge

During EFA high flow survey there were some troubles for the discharge measurement at het Pool section because of the range of the Bluetooth. The Riffle section contained standing waves, which are difficult for the River Surveyor to cross. During the EFA low flow survey the riffle section consisted of a big rapid with a lot of standing waves, where we could not measure one cross section (T5). Some stones were present in other cross sections, causing the track of the River Surveyor to deviate.

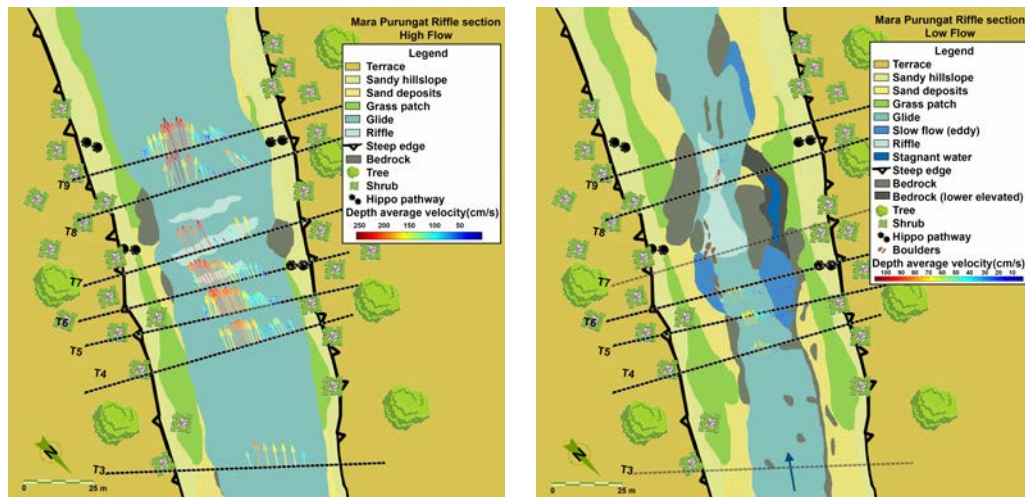
C.2.3. Cross sectional profile

During the EFA high and low flow survey the cross sections were made. During the high flow survey this was done using a Total station for the dry cross section, and during the low flow survey a DGPS was used for the dry cross section. All 9 cross sections upstream (2) and downstream of the bridge(7) were measured during high flow survey. During low flow survey only 1 cross section upstream and 5 cross sections downstream could be measured due to the signal received from the DGPS.

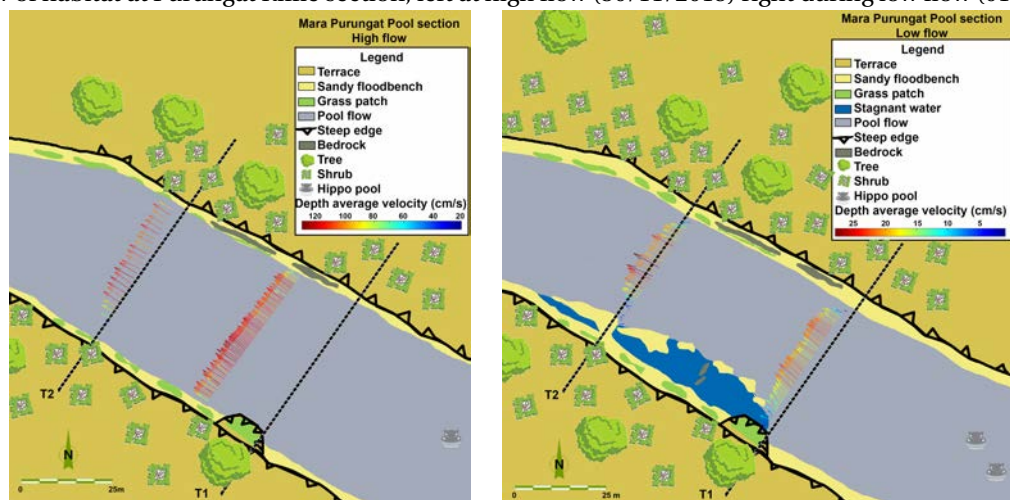
During high flow survey at the downstream site, the water level was measured with the total station over a distance of 58 m, and was 0.00226 m/m. During low flow survey, the water level was measured with the DGPS over a distance of 274.5 m and was 0.0025 m/m. During the monthly monitoring survey there was no equipment to measure the slope of the water level. For the site in the pool section during high flow the measurement of water level was done over a distance of 160 m with a slope of 0.0004 m/m.

C.2.4. Sediment analysis

Samples were collected along the banks, floodplain and flood zone (in the river). There was no possibility to get bed samples due to the high water level and the fast flow at the bridge. During the low flow survey, there was possibility to go into the water cautiously, beware of the hippos. There we found that the bed sediment



Planview of habitat at Purungat Riffle section, left at high flow (30/11/2015) right during low flow (01/03/2016)



Planview of habitat at Purungat Pool section, left at high flow (01/12/2015) right during low flow (29/02/2016)

Figure C.8: Planview of habitat at Purungat Bridge. Upper: Riffle section, downstream of the bridge;
Lower: Pool section, upstream of the bridge

was mainly bedrock, with some pockets with coarse gravel. There were vegetated flood benches present. But also bank slumping of the terrace banks could be seen.

There were 3 samples for Purungat bridge taken home, two for the upstream pool section, of both banks a sample from 1m of the water edge, and the sample downstream, which can be described as a gravel pocket. One of the upstream samples could not be analysed because the sample was too small. Clast counting has been done for pebbles in the bedrock area at the right hand bank, close to the gravel pocket. The material found at the left bank during low flow can be classified as boulders over bedrock.

Suspended sediment The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature, see Table C.7.

Table C.5: Discharges and velocities for Mara Purungat hydraulic measurements

Date	Section	Discharge (m^3/s)	Maximum velocity (m/s)	Mean velocity (m/s)
30-11-2015	Riffle	96.403	3.11	1.337
01-12-2016	Pool	75.017	1.72	1.267
08-01-2016	Monthly	17.650	1.7	0.148
29-02-2016	Pool	6.179	0.54	0.163
01-03-2016	Riffle	5.505	1.28	0.485

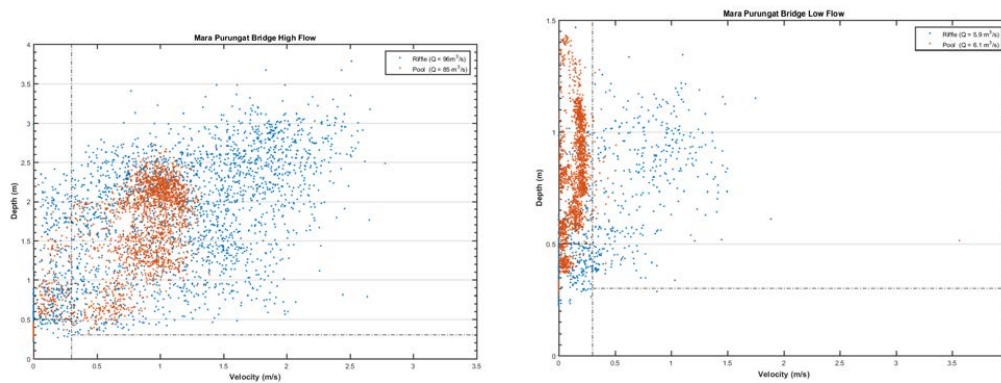


Figure C.9: Velocity depth graph Mara Purungat Bridge. Left: High flow; Right: Low flow

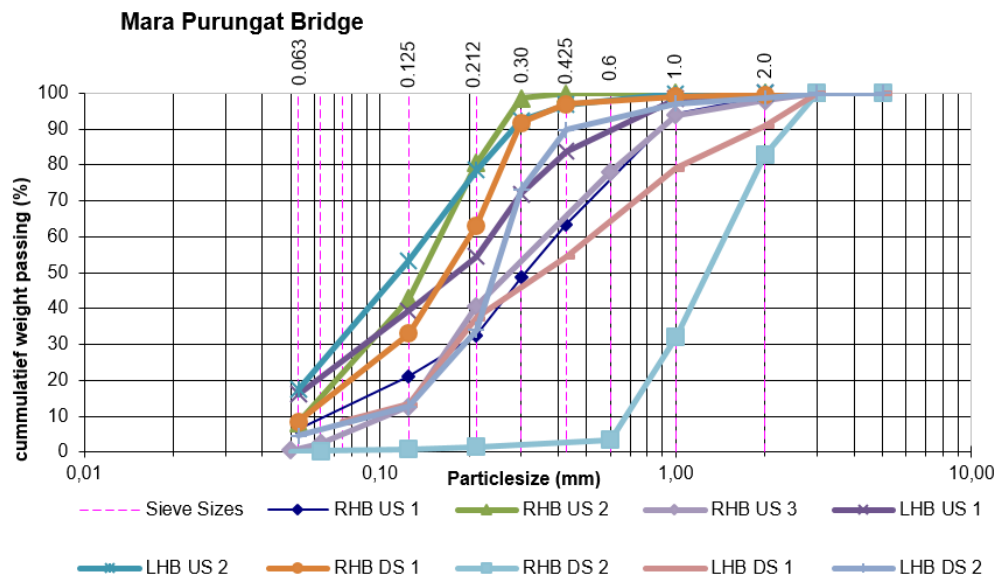


Figure C.11: Sediment distribution for samples at Purungat Bridge.

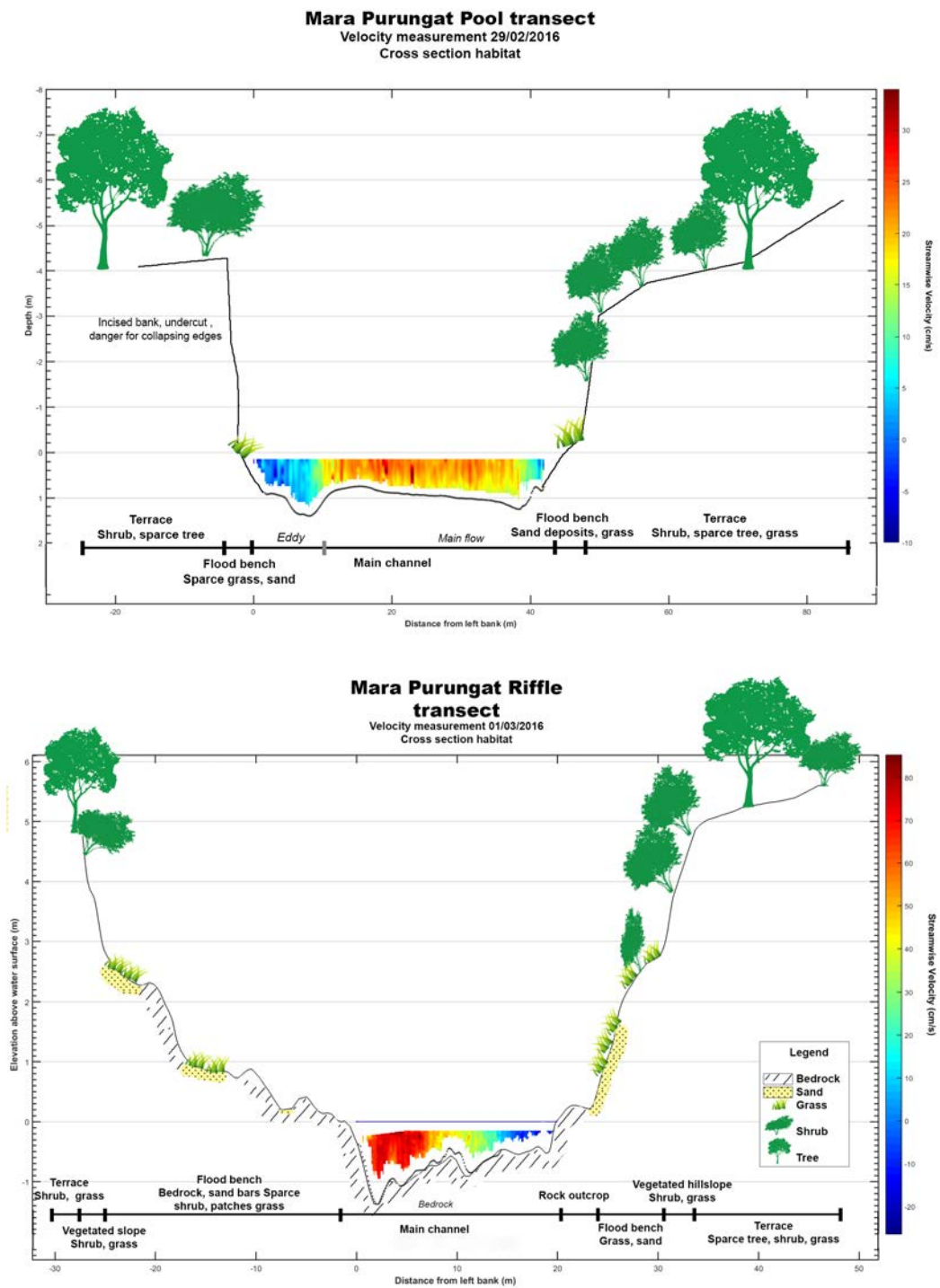


Figure C.10: Cross section habitat with velocity measurement during low flow.

Table C.6: Characteristic size of sediment (D_{50}) at Mara Purungat Bridge

Sample	D_{50} (mm)	Remarks
Upstream (pool section) RHB Bank material	0.298	
Upstream (pool section) RHB Flood deposits	0.139	
Upstream (pool section) LHB Bank material	0.181	
Upstream (pool section) LHB Flood deposits	0.115	
Downstream (riffle) RHB Flood zone	0.17	
Downstream (riffle) LHB flood zone	0.245	
Downstream (riffle) LHB Bank material	0.355	
Downstream (riffle) LHB Parent soil	0.217	
Low flow, downstream, RHB	1.5	
Low flow, upstream, 1m from water edge	0.29	

Table C.7: Suspended sediments at Mara Purungat Bridge

Q (m^3/s)	Turbidity (NTU)	SS (mg/L)	Source
96.4	508	500	Field measurement
75.017	401	600	Field measurement
5.505		119	Field measurement
17.650	189	166.67	Field measurement

C.3. Emarti

05/12/2015 - 16/12/2015 - 09/01/2016 - 27/01/2016 - 05/03/2016

The EFA site near Emarti bridge differed from the previous EFA site near Emarti bridge, which was Safari Club. The Safari Club site was visited during the high flow survey, but found not feasible enough due to wildlife presence and difficulty to get to the other side of the river. So the site for this EFA survey was chosen to be Emarti at Mara Beef farm, just upstream of the Emarti bridge, where also a gauging station is located where monthly monitoring of discharges takes place. This site is as can be seen in Figure 17 surrounded by pivot irrigation schemes, and also by Mara Beef farm, where cows are farmed. The river at the site is generally very incised, and at Mara Beef also the left hand bank is prone to degradation due to cattle grazing. At the Mara Beef site, EFA 2016, two transects were measured, one across a riffle, and the other one across a pool section. During Monthly monitoring the cross section for Emarti gauging station was tended to be measured, but due to high flows, there was little accessibility to use the River surveyor, and also little visibility due to the vegetated banks made the measurement of cross section too difficult. It was however possible to measure the water level slope. During the EFA low flow survey the cross section was then obtained with the DGPS. Also during EFA low flow survey the oxbow lake was visited, which can be seen in Figure 18. Also an attempt to measure the height differences between the bed of the oxbow and the current water level was undertaken, but due to too much vegetation the GPS receiver could not get a signal which was good enough to do this. Only a few height differences are measured.

The Emarti bridge was over topped in the flood of 1997 (personal comments Joseph, teacher in area of Emarti bridge), when animals died. Usually the area drains the water quickly to the river, so people don't have big problems with flood season, although the area is quite flat. Also, during the visit of 16/12/2016, deposits were found on the bridge itself, indicating that the level had recently been up to the bridge, confirmed by people in the area, and the fact that at Kichwa Tempo the bridge was also flooded in the night of 15/12/2016. So the measurements of 16/12/2016 were during the falling limb of a flood peak.

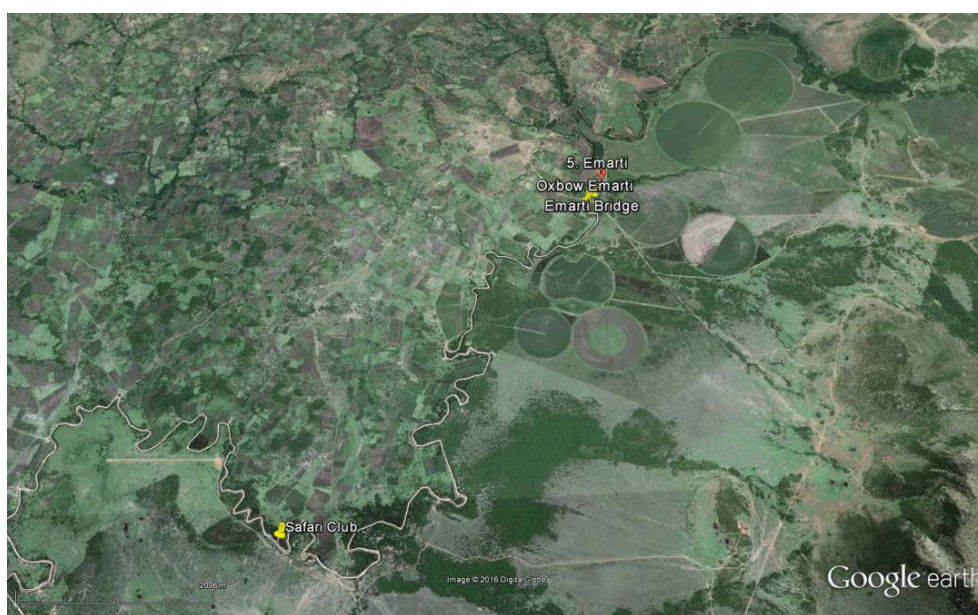


Figure C.12: Overview of the site at Emarti Bridge from Google Earth.

C.3.1. Habitat Mapping

Emarti Bridge Just upstream of the bridge, the river comes out of a, and downstream of the bridge, the river is very straight and incised, the difference between the terrace and the water level at low flow is 10 meters. The flow is very confined here, and bedrock has been hit in the middle of the channel. The banks are consisted of consolidated soil, the right hand bank is undercut, above this zone, the shrub begin to grow. The left hand bank is more vegetated, with sparse grass and sparse shrub, this is a less erodible shelf, consisting of consolidated soil/bedrock. At the right hand bank, just downstream of the bridge, coarse deposits in the form of cobble is identified from pictures of ... taken by Anne Liliande. During the visit at 16/12/2015, the shrub at

the right hand bank under the bridge was partly submerged. From the velocity-depth diagram in Figure C.16, it can be seen that the pattern for low and high flow is the same; for both flows, there is slow-shallow habitat, no fast-shallow habitat, and mainly deep-fast habitat. This can be explained by the fact that the channel is very confined, and flows are not very much reduced in speed or depth during high or low flows. A special remark for this site is that during the survey, two men were fishing around T1, and they caught quite big fish. This is a resource for them, they sell the fish at the market, but not many people eat the fish in the area.

Mara Beef The river has cut through the banks here, and therefore, a strange pattern of bends can be observed. The incision here is around 11 meters. Remnants of consolidated soil and bedrock are observed in the form of a flood shelf during the low flow, at the right hand bank between T1 and T2. Around the edge of this shelf with the water, a lot of grass is growing, and in the end of the shelf a shrub is growing. Just before this shelf, on the right hand bank, a sandy flood bench followed higher up the cross section by a dense vegetated flood bench are situated. The left hand bank consist of a degraded banks just before T1, caused by cattle (cows) watering here daily. Then, at T1 on the left hand bank, a densely vegetated flood bench with a steep bank towards the waterline is located. In this outer bend, vegetation an undercut banks provide coverage of the instream habitat. Just before T2 the bank is highly degraded, goats water here, no shrub or grass is found, the bank only consists of consolidated soil. Downstream of T2, the river is restored again, with vegetated left and right hand banks, including the flood benches, overhanging the riverine habitat.

During high flow, the water over the riffle flows straight to the south, and high flow velocities scour the outer bend at T2. During low flow, the water flows over the riffle in south-east direction, and high flow velocities in the outer bend after T1 scour the flood bench at the left hand bank downstream of T1. During low flow, a lot of grass patches along and a few in channel are found, see Figure C.14, left figure.

This provides the following habitats:

Highflow:

Riffle; fast-deep

Eddy; woody debris

Plain bed/ regime flow

Eddy2; overhanging vegetation

Coarse bedmaterial

Grass and shrub instream

Low flow:

stagnant water; shallow pool; eddy; over sand

glide and runs over coarse bed material; cobble and boulder

pool flow over sand

Velocity-Depth graphs From the velocity-depth diagrams (Figure C.15), it is shown that the pool section is much deeper than the riffle section, and that the velocities in the riffle section are more widespread both during high and low flow. Velocities in the pool are higher during high flow, because the channel is more confined here, and vegetation along the right hand bank provides a part where the flow is slower. During low flow, the velocities in the pool transect are more confined.

- River has cut through the part downstream T1.
- Remnants of consolidated soil are still seen in the shelf at low flow
- Outer bend after T1 is eaten away; steep slope here.
- Degraded hill slopes because of cattle trampling(cow farm, goats); at 3 spots; major one on the south bank before T2.
- Agriculture on the east side of the river; at the right hand bank.
- Incision 11 m (distance from terrace to channel bed).
- Upstream T1 proper flood benches are distinguished. After T2 the river is a bit more incised, but the banks are more vegetated.

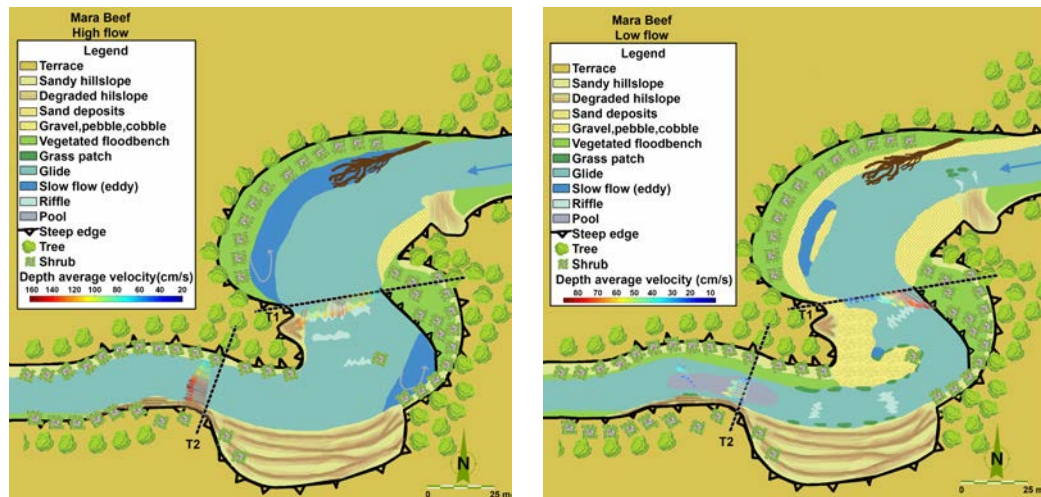


Figure C.14: Planview of habitat at Mara Beef, upstream of Mara Emarti Bridge. Left: High flow; Right Low flow survey.

- Shrub in the middle of the river; apparently this one can survive. It also must have had the chance to grow.....! What can we say about this?
- Grass patch also found upstream of T1.
- T2 is deep; pool-ish flow; laminar T1 is on top of bedrock/ cobble & boulder.
- Shadow in outer bend after T1.
- Habitat types: Eddy over sand; deep and shallow, in the "shadow" of the dead tree; habitat for mi and fish. Riffle over cobble, outerbend with shadow (and eddies in highflow). After bend poolish flow over sand; deep.

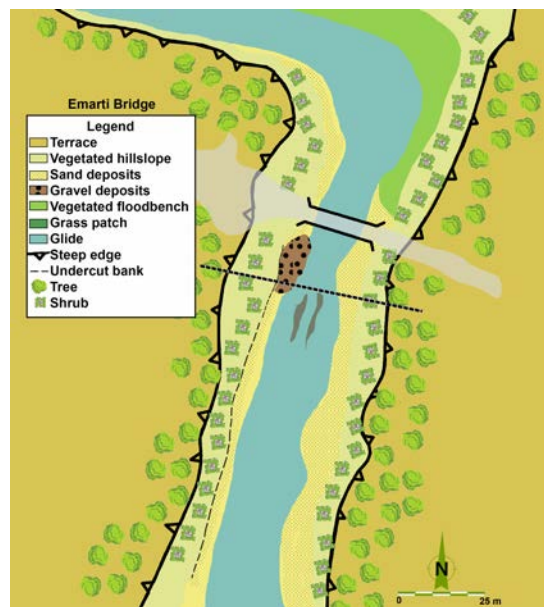


Figure C.13: Planview of habitat at Mara Emarti Bridge, during low flow

C.3.2. Discharge

During the EFA low flow survey the water was wade-able, but the river surveyor was used during low and high EFA survey for both transects. During the monthly monitoring in December 2015, it was not possible to use the River Surveyor, due to the high flows there was a high risk of losing the device. So then we did the floating method. In January 2016 the river was very low. During high flow the water level was measured over a distance of 150 m and the slope of the water level was 0.00124 m/m.

Table C.8: Discharges and gauge heights measured at Mara Emarti Bridge and Mara Beef. * Estimated with the floating method.

Gauge height (m)	Date	Discharge (m^3/s)	Site	Survey
-	05-12-2015	53.865	Mara Beef	EFA high flow
4.15-3.89	16-12-2015	131*	Emarti Gauging	Monthly monitoring
1.50	09-01-2016	14.037	Emarti Gauging	Monthly Monitoring
-	05-03-2016	4.729	Mara Beef	EFA low flow

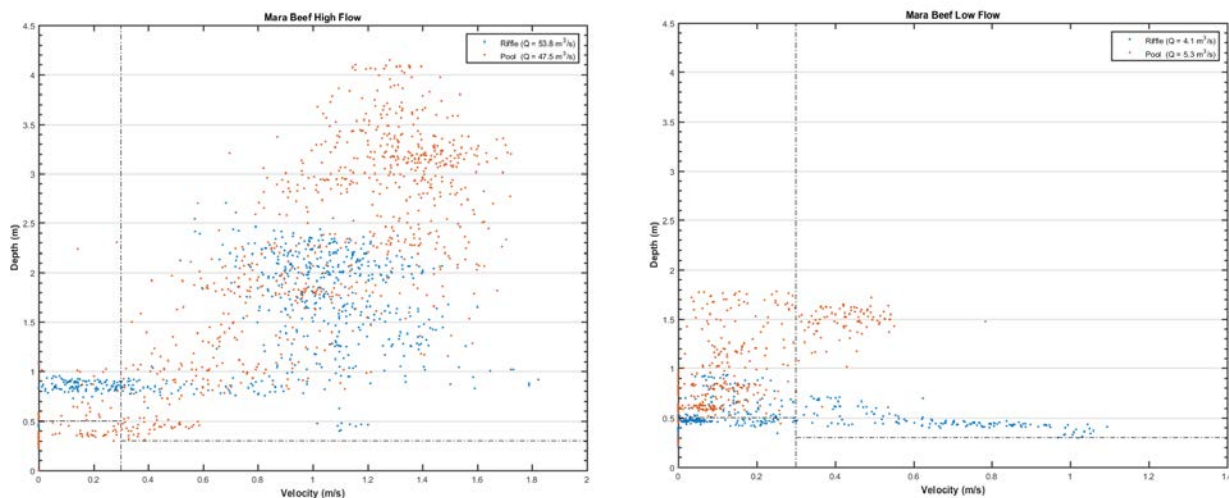


Figure C.15: Velocity depth graph Mara Beef. Left: High flow; Right: Low flow

C.3.3. Sediment analysis

During EFA high flow survey, sediment samples were taken along the channel, and one grab sample was taken in a pool just upstream of Transect 1. Here we also found an oyster. During EFA low flow survey sediment samples were taken from the flood benches at both sides of the river, and from an inset flood bench. Furthermore, it was possible to examine the bed material, which was mainly pebble and cobble. Also on the inner bend the bed material was of all different sizes gravel and pebbles. At Emarti bridge, during monthly monitoring it was unfortunately not possible to get a bed sample, although, during the DGPS transect, mainly cobble, boulder and bedrock was felt along the transect (just downstream of the bridge). There are two samples of deposition taken; from both banks. RHB 1 from higher up the cross section at the right hand bank, and RHB 2 taken flood deposits from lower at the cross section.

Suspended sediment The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature.

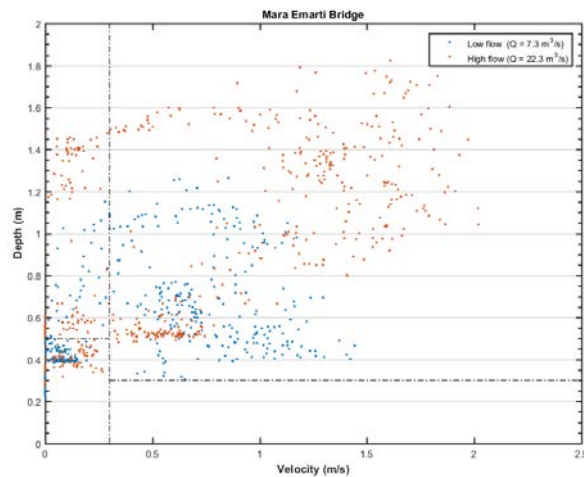


Figure C.16: Velocity depth graph Mara Emarti Bridge for low flow and high flow

Table C.9: Discharges, mean velocities and width of the river at Mara Emarti. *Velocity of the floats ** Floating method; depth 4m, area 72m2, velocity 2.6, depth averaged velocity 2.6×0.7 makes: $72 \times 2.6 \times 0.7 = 131 \text{ m}^3/\text{s}$.

Date	Survey	Discharge (m^3/s)	Mean velocity (m/s)	Maximum velocity (m/s)	Width (m)
05-12-2015	EFA High Rifle	53.785	0.966	1.94	32.881
05-12-2015	EFA High Pool	47.535	1.141	2.08	16.268
16-12-2015	Monthly Moni.	131**	2.60*		20
09-01-2015	Monthly Moni.	14.022	1.035	2.01	12.108
05-03-2016	EFA Low Rifle	4.050	0.375	1.09	28.088
05-03-2016	EFA Low Pool	5.26	0.295	0.93	14.001

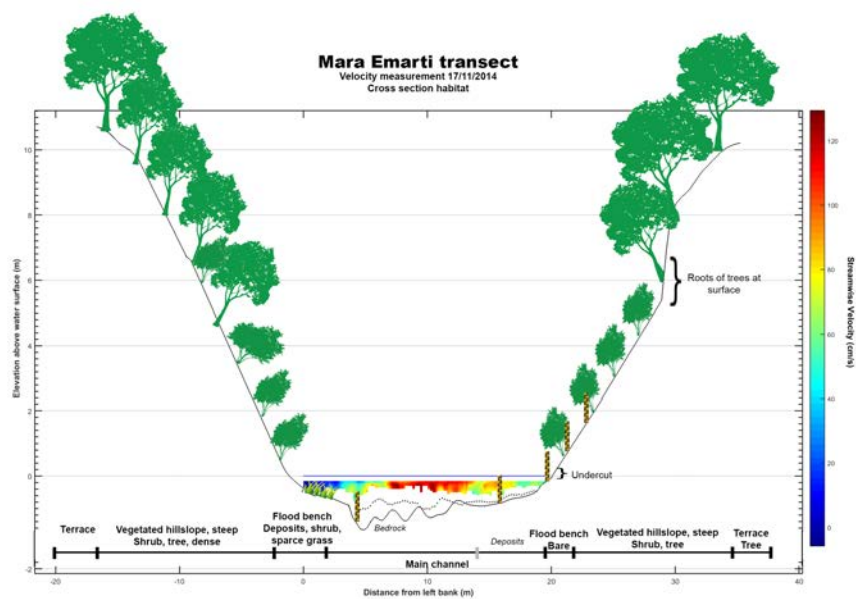


Figure C.17: Cross section habitat at Mara Emarti Bridge, with velocity measurement during low flow.

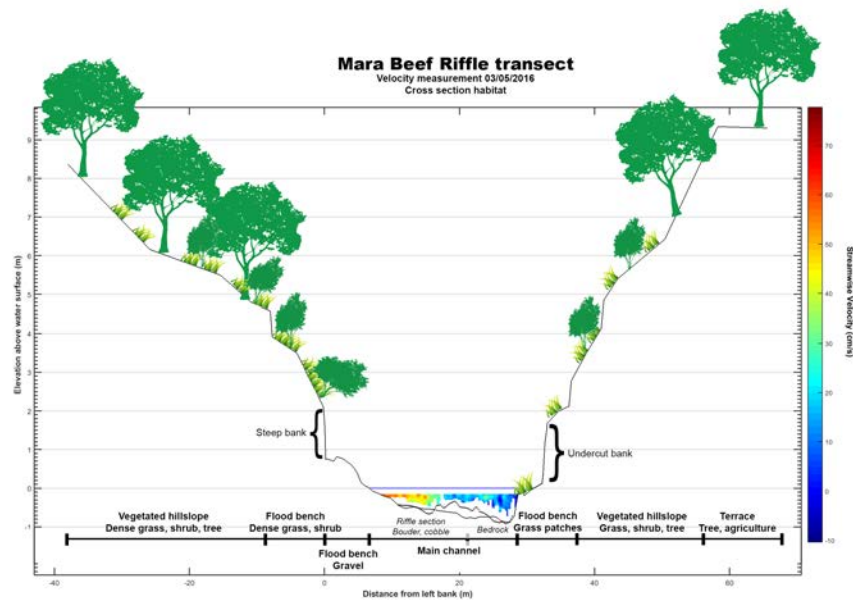


Figure C.18: Cross section habitat at Mara Beef, riffle transect, with velocity measurement during low flow.

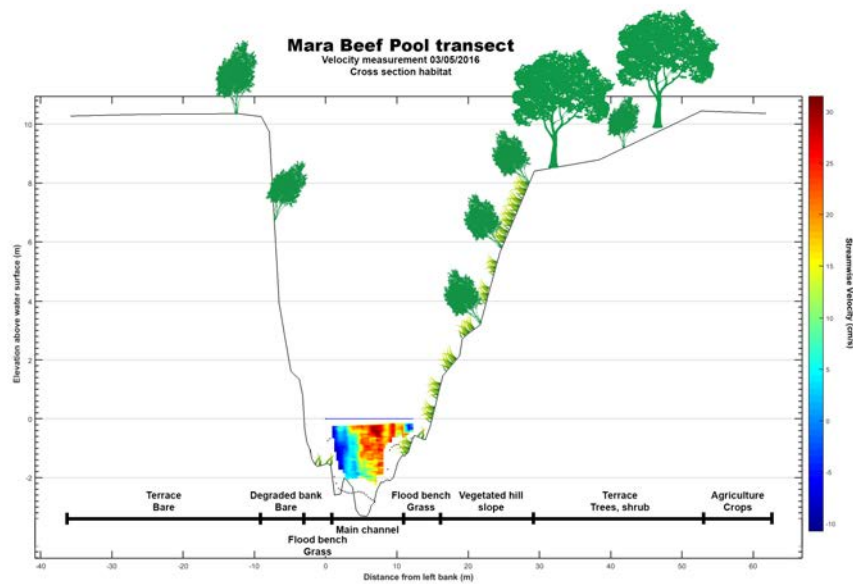


Figure C.19: Cross section habitat at Mara Beef Pool transect, with velocity measurement during low flow.

Table C.10: Values for suspended sediment measurements from the field survey, and from literature.

Discharge (m^3/s)	Turbidity (NTU)	SS (mg/L)	Source
47.535	184	225,204	Field measurement
131	767	933.33	Field measurement
14.022	67.2	50	Field measurements
5.26		32.8	Field measurements
0.3134	54.6		Masese, 27-28 March 2015

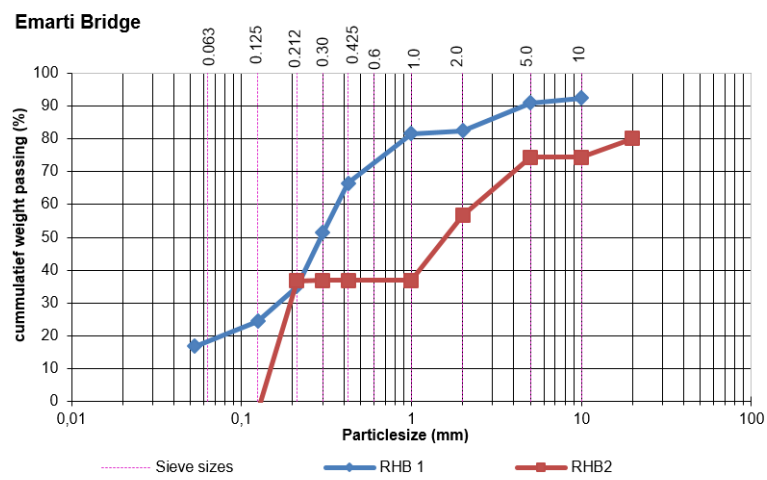


Figure C.20: Sediment distribution of samples from Mara Emarti Bridge

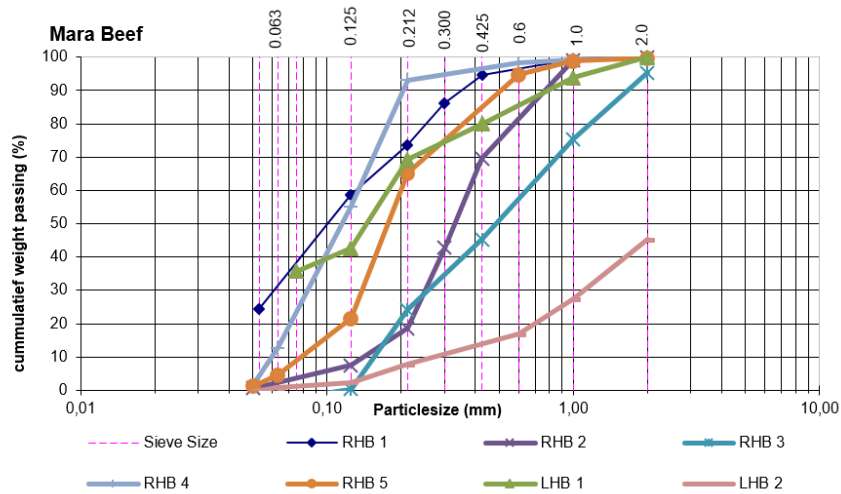


Figure C.21: Sediment distribution of samples from Mara Beef

C.4. Kichwa Tempo

15/12/2016 - 09/01/2016

This reach is located just upstream of the area where the meanders are starting, and is close to the Siria Escapement. On the right hand side of the river this escapement can clearly be seen in Figure 48. This site also has gauging station where the gauge height is read twice a day. The records originate from 1970, but there are many gaps in the data. This data is considered not fit for hydrological analyses (Nile Basin Initiative (NBI), 2014; Hulsman 2015). Nevertheless, it is an important site to monitor, since it is the last gauging station in Kenya before the border with Tanzania. The gauging station is located at the left bank, downstream of the Old Mara Bridge (Figure C.22). The discharge measurement for the monthly monitoring is usually done upstream of the bridge, because it is easily accessible and the and also downstream of the bridge, near the gauging station a hippo pool is located. A new gauge reader (Justin) was engaged during the December monitoring. The bridge was that night before overflowed, there fore a lot of debris was found during the field visit of 15/12/2016. So the measurements of 15/12/2016 were during the falling limb of a flood peak.

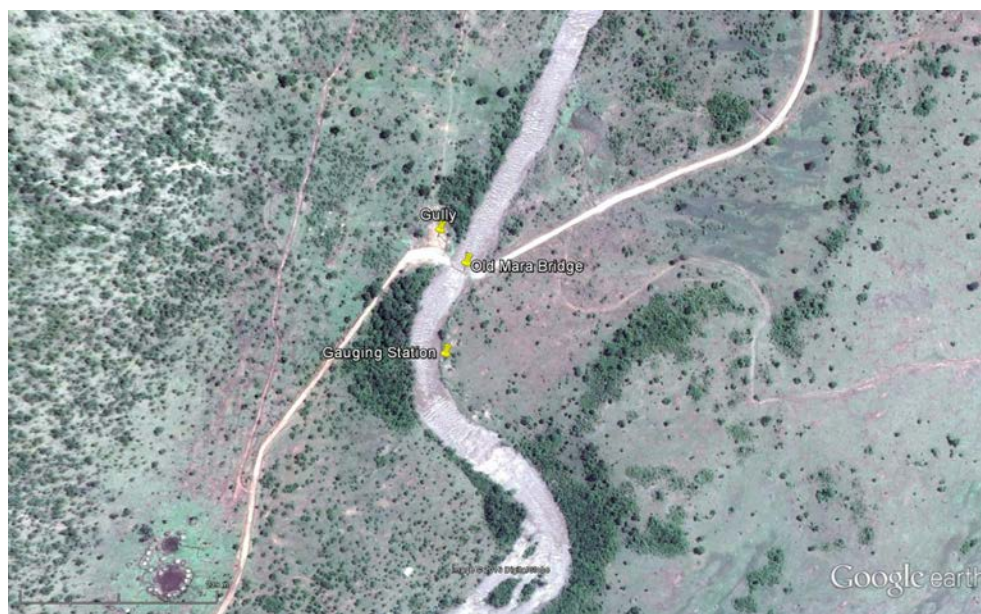


Figure C.22: Site overview of Mara Kichwa Tempo from Google Earth

C.4.1. Habitat Mapping

Bed material is predominantly boulder and cobble (Figure C.24). During the fieldwork, in December and January, riffle flow was observed upstream of the bridge, downstream of the bridge hippo pools are present. No signs of hippos upstream of the bridge, since the water level is expected to be low most of the time due to the width of the channel and the gradual slope of the left bank. The channel is quite straight, but the right bank is more vegetated and steeper than the left bank, where flood benches are present with shrub and trees. This bank is less vegetated than the right bank. Sand pockets are found on the left hand bank, while the right hand bank slope is steeper, and densely vegetated flood benches are distinguished more upstream. Close to the bridge, the right hand bank is collapsing due to its steepness and probably the waves exiting on the bank. Woody debris was available in the sense of branches from shrub, and during the high flow (15/12/2015), a tree was stuck underneath the bridge. On land at the right hand side, a big gully is found, which seems to be created from overland flow.

Velocity-Depth graph From the velocity-depth graphs it can be seen that the velocity ranges are quite large for both high and low flow. For the high flow there is some part of the river shallow-slow, but in the low flow survey this was not found. However, due to the way of measuring with the RiverSurveyor (this habitat will not be measured quickly. However, during the low flow survey, the deep-fast part of the low flow measurement is close to the shallow-fast part. But most of the habitat measured with the RiverSurveyor, is deep-fast.

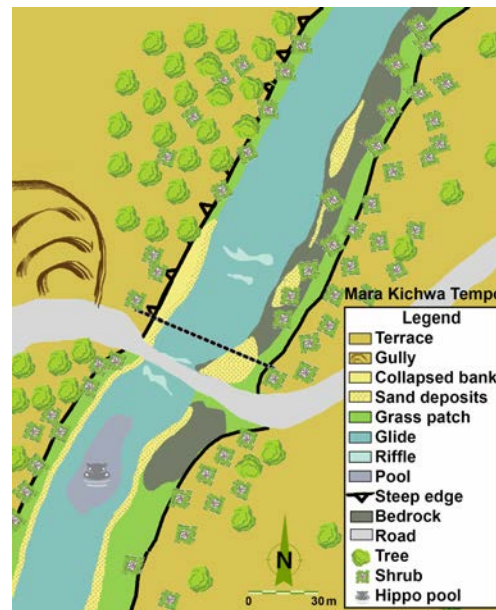


Figure C.23: Plan view of the habitat seen at Mara Kichwa Tempo 09/01/2016



Figure C.24: Impression of the bed at Mara Kichwa Tempo, picture taken by Anne Lilande on 27/03/2015.

C.4.2. Discharge

The discharge measured during the monthly monitoring in December was 82.973 m³/s, with corresponding measurement of water level slope of 0.003147m/m over 213m. In January the measured discharge was 15.592m³/s.

Table C.11: Discharges and velocities measured at Mara Kichwa Tempo with corresponding gauge heights.

Date	Gauge Height(m)	Discharge (m ³ /s)	Mean velocity (m/s)	Maximum velocity (m/s)	Width (m)
15-12-2015	1.50	81.891	1.035	2.14	46.514
09-01-2016	0.90	15.56	0.696	1.25	28.645

C.4.3. Cross section

C.4.4. Sediment analysis

In December sediment samples of both left bank and right bank were taken for flood deposits and bank material. In January three samples of deposited sediments were taken, one for left bank and two for the right bank; upstream and just downstream the bridge. In December attempts were made to get a grab sample from the bridge on the lee side, since there the grab sampler could reach the bottom without flowing away. Only one stone was sampled, which is not strange, knowing that the bed is very irregular, consists of mainly boulders, with sand and gravel pockets.

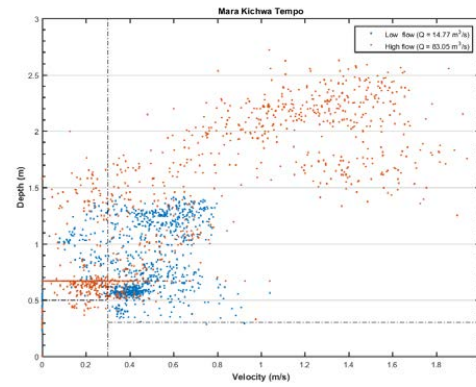


Figure C.25: Velocity depth graph Mara Kichwa Tempo at high and low flow

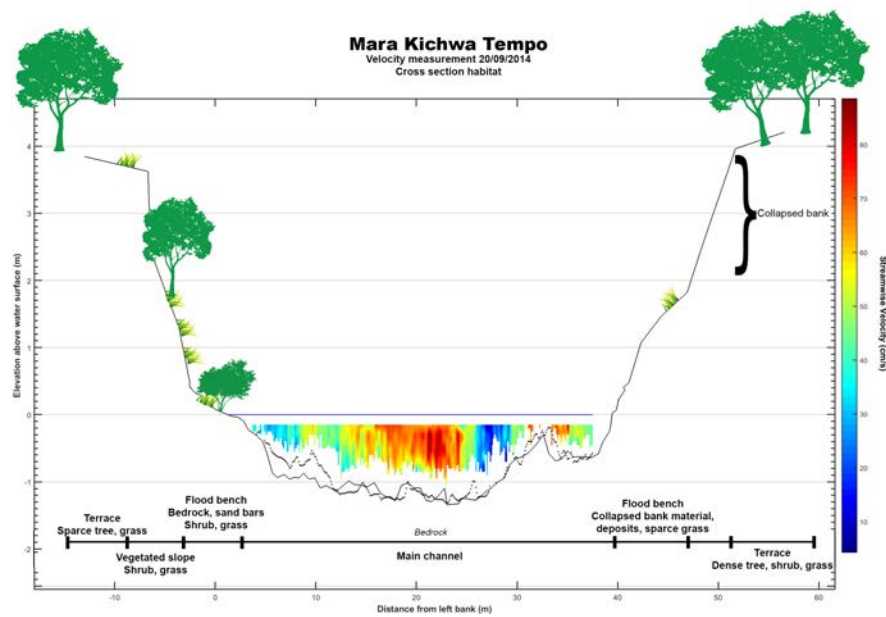


Figure C.26: Cross section habitat at Mara Kichwa Tempo, with velocity measurement during low flow.

Suspended sediment The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature.

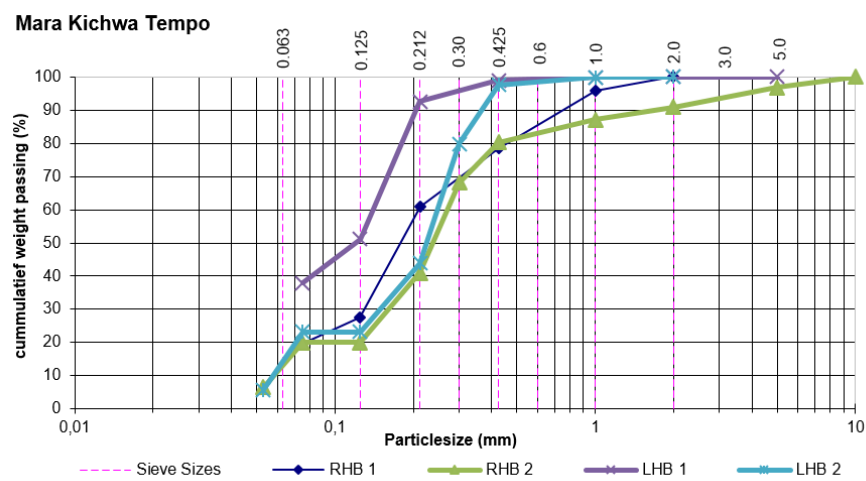


Figure C.27: Sediment distribution of samples at Mara Kichwa Tempo

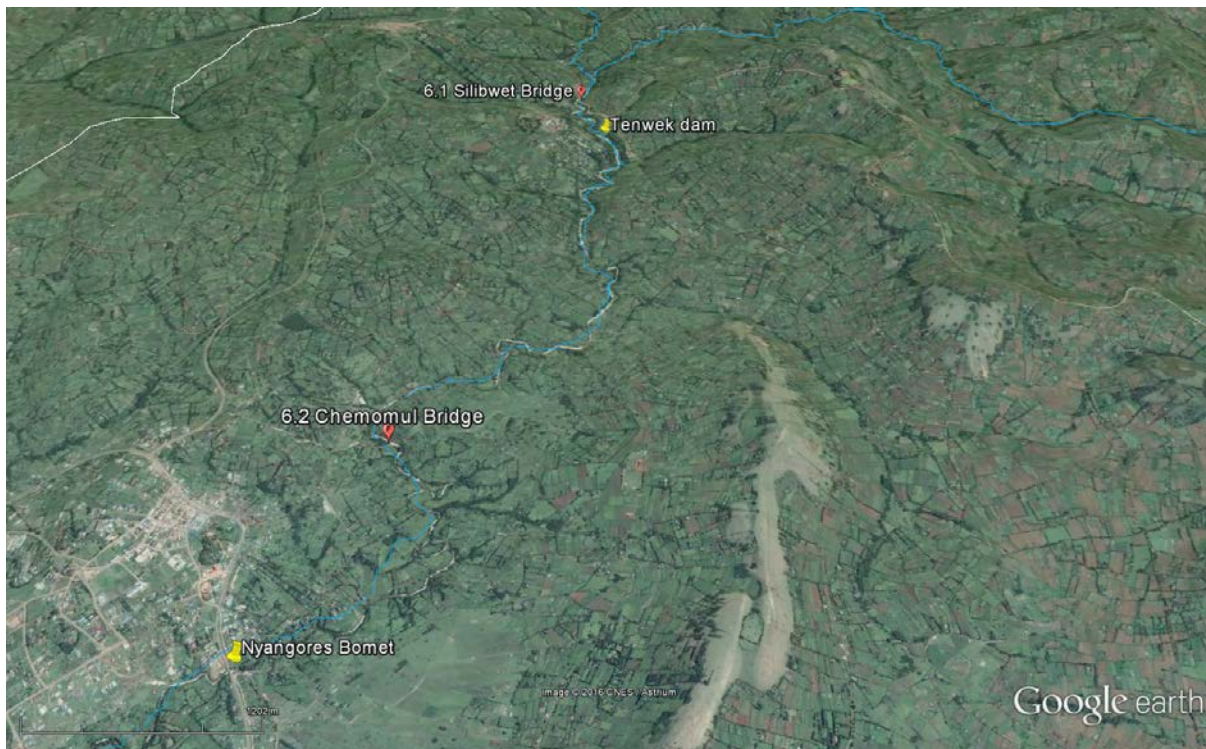
Nyangores Silibwet

06/12/2015 (EFA high flow)

10/01/2016 (Monthly Monitoring)

07/03/2016 (EFA low flow)

The Nyangores site was split up into two sites, because of the presence of the Tenwek dam which supplies hydropower to the Tenwek Hospital. The Silibwet site is upstream of the Tenwek dam, just after two tributaries from the Mau forest join. The Chemomul site is located downstream the Tenwek dam, and the monthly monitoring site is located even further downstream, in the town of Bomet. Both the EFA sites are surrounded by small agricultural farmers, as can be seen in the planviews. These sites have a more mountainous stream character, and do not show signs of incision. Also during the EFA high flow survey, we visited the Mau forest and the tea farming which create a band around the forest. During the monthly monitoring in January we had enough time to go back to the Silibwet site to measure again the discharge.





Discharge measurement

At Nyangores Silibwet we surveyed 4 transects. During EFA high flow survey 4 discharge measurements were made with the River Surveyor, as was the case during the monthly monitoring. During the EFA low flow survey measurements were done with the River Surveyor, but also with a hand held velocity meter and the flow tracker to validate those measurements for turbulent flow. During monthly monitoring survey we had no equipment to measure the water level slope. For the low flow survey, there are two slopes noted in the table below, one measured over a distance of 162 m, and the other one measured over a distance of 101 m. The latter one was measured from just upstream a rapid till the downstream point, the first slope is measured as far away as was possible.

Date	Survey	Discharge (m ³ /s)	Slope (m/m)	Distance for slope measurement (m)
06-12-2015	EFA high flows	29.947	0.00636	99
10-01-2016	Monthly Monitoring	7.893	-	
07-03-2016	EFA low flows	1.777	0.00598	162
			0.00736	101

Date	Transect	Discharge (m ³ /s)	Mean velocity (m/s)	Maximum velocity (m/s)	Width (m)
06-12-2015	T1	29.367	1.358	2.32	19.706

06-12-2015	T2	30.596	1.439	2.53	19.928
06-12-2015	T3	31.827	1.5	2.25	21.372
06-12-2015	T4	27.945	1.524	2.55	20.119
10-01-2016		7.662	0.653	1.24	18.944
07-03-2016	T1	2.275	0.284	0.73	18.405
07-03-2016	T3	2.017	0.246	0.81	19.917
07-03-2016	T4	1.848	0.234	1.37	19.803

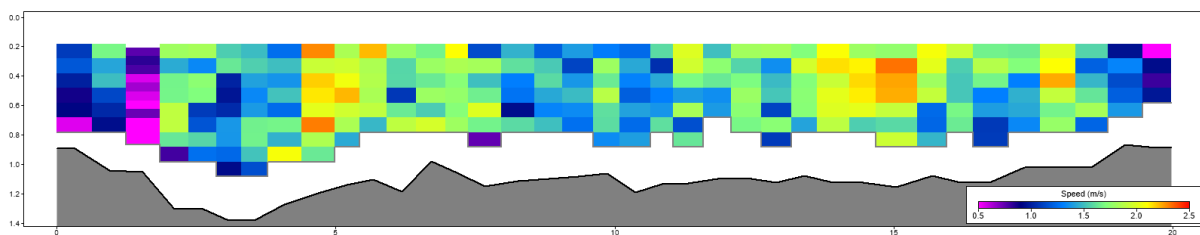


Figure 1 High flow velocity profile Nyangores Silibwet T1

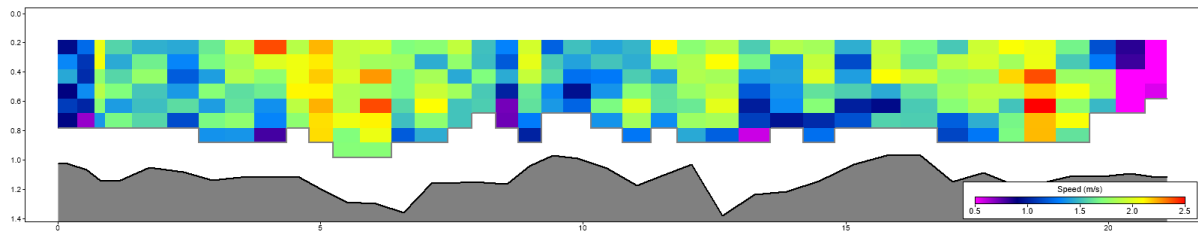


Figure 2 High flow velocity profile Nyangores Silibwet T2

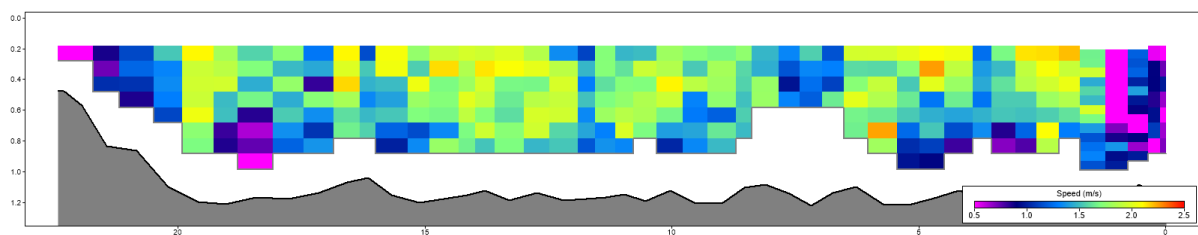


Figure 3 High flow velocity profile Nyangores Silibwet T3

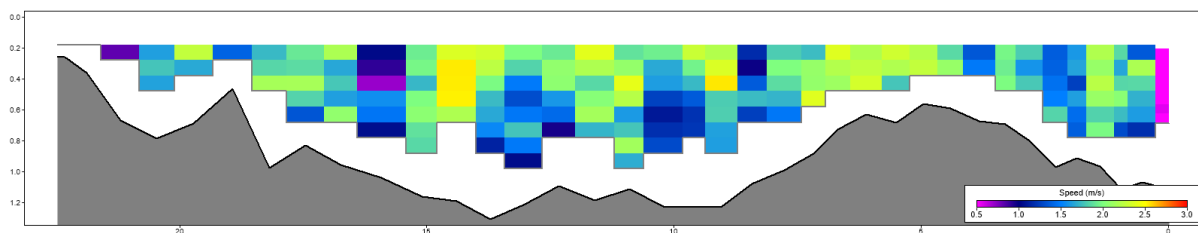


Figure 4 High flow velocity profile Nyangores Silibwet T4

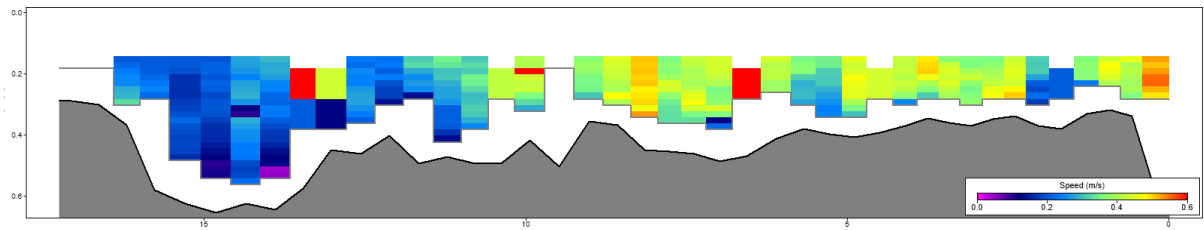


Figure 5 Low flow velocity profile Nyangores Silibwet T1

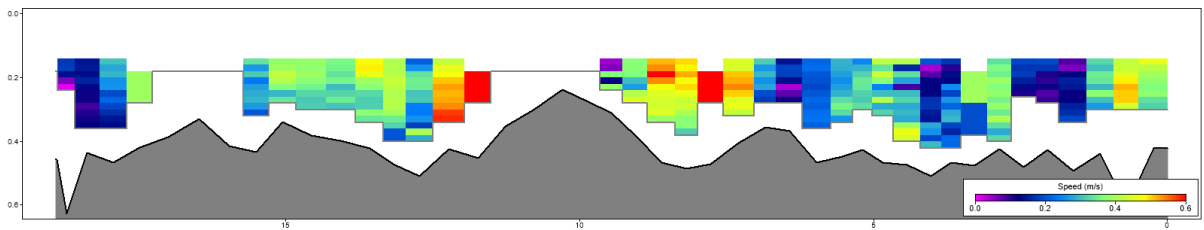


Figure 6 Low flow velocity profile Nyangores Silibwet T3

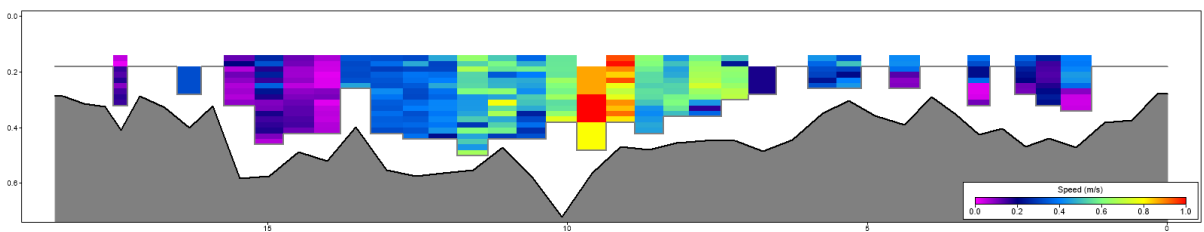


Figure 7 Low flow velocity profile Nyangores Silibwet T4

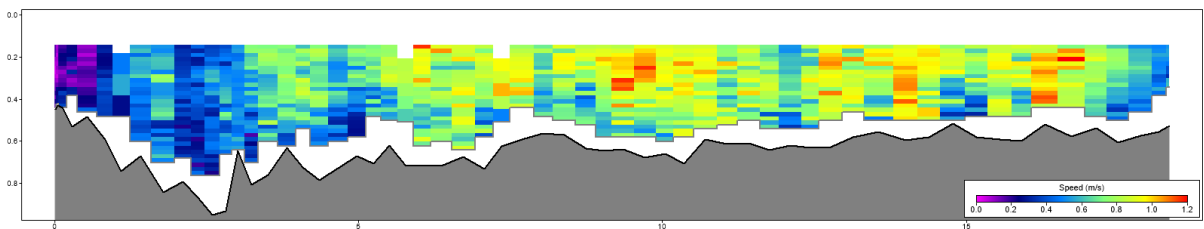
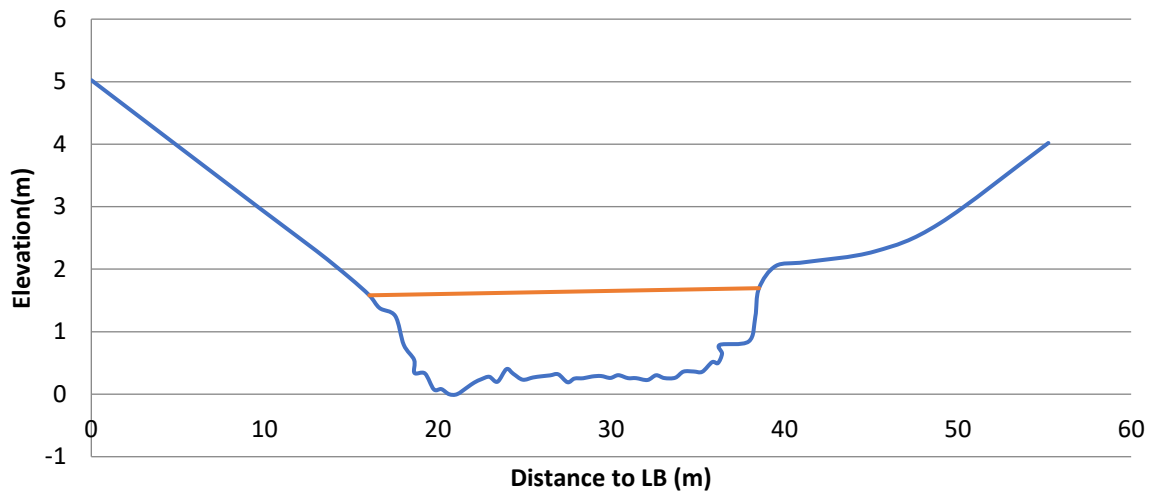
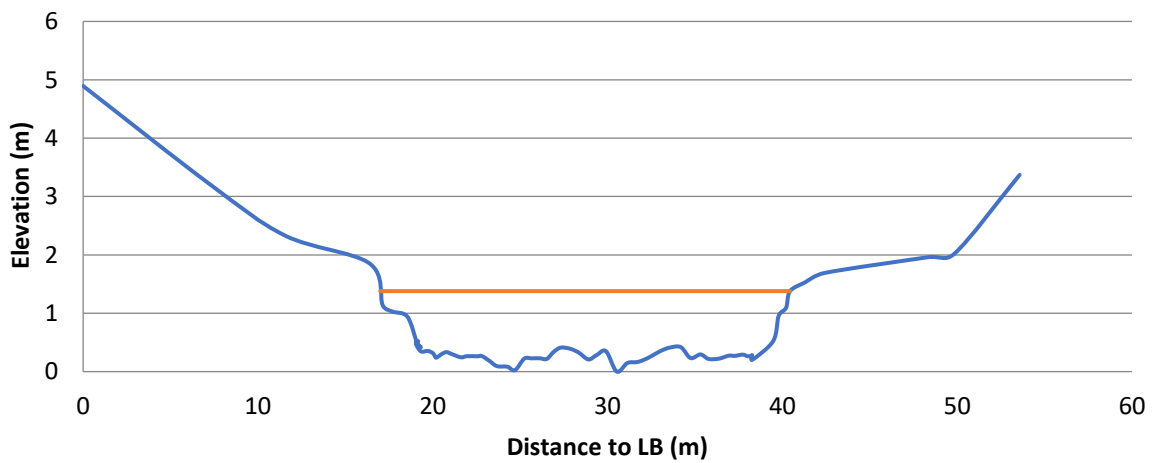
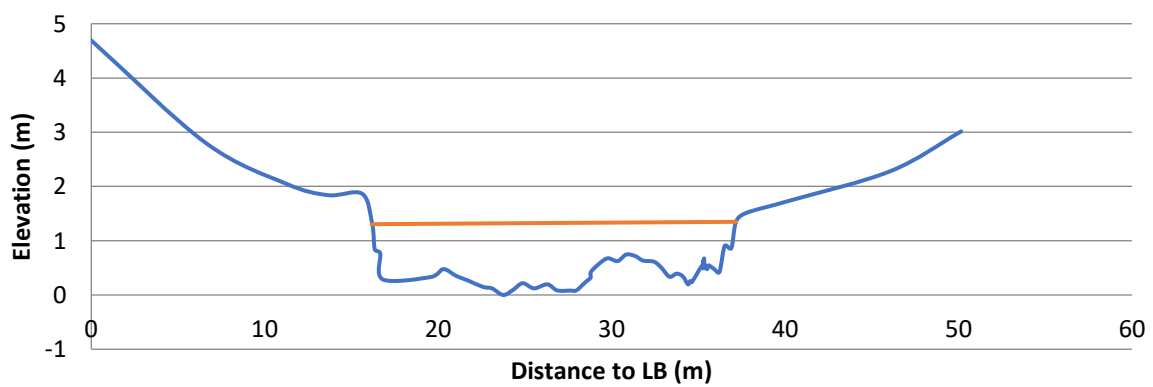


Figure 8 Flow velocity Nyangores Silibwet monthly monitoring

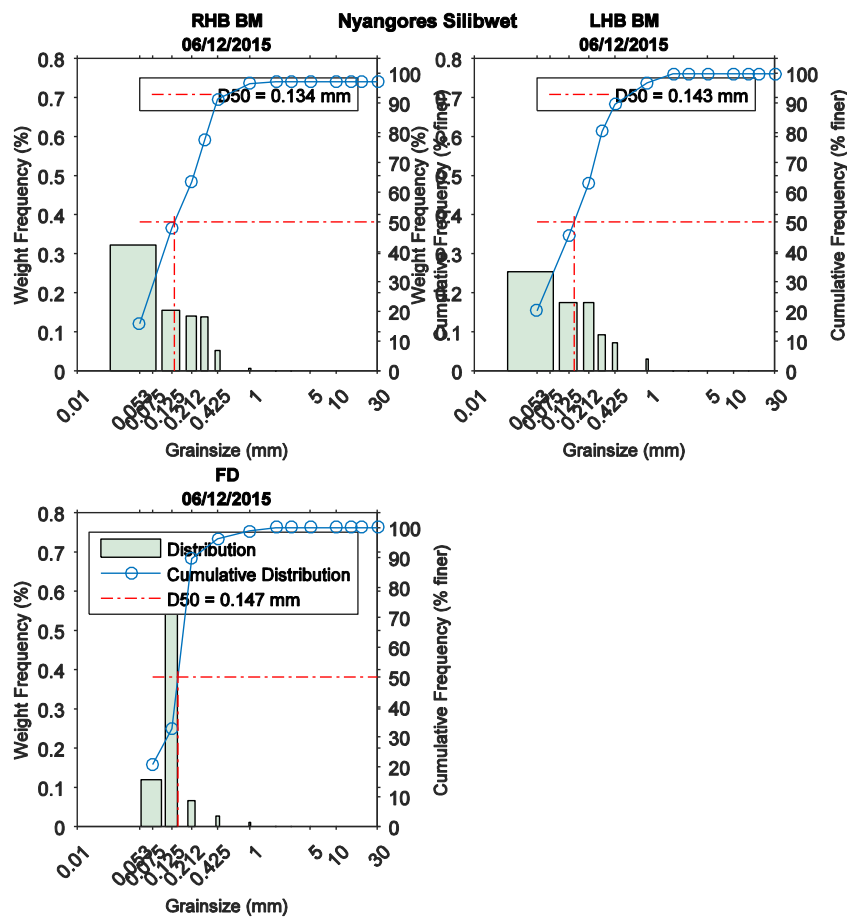
Cross sectional profile

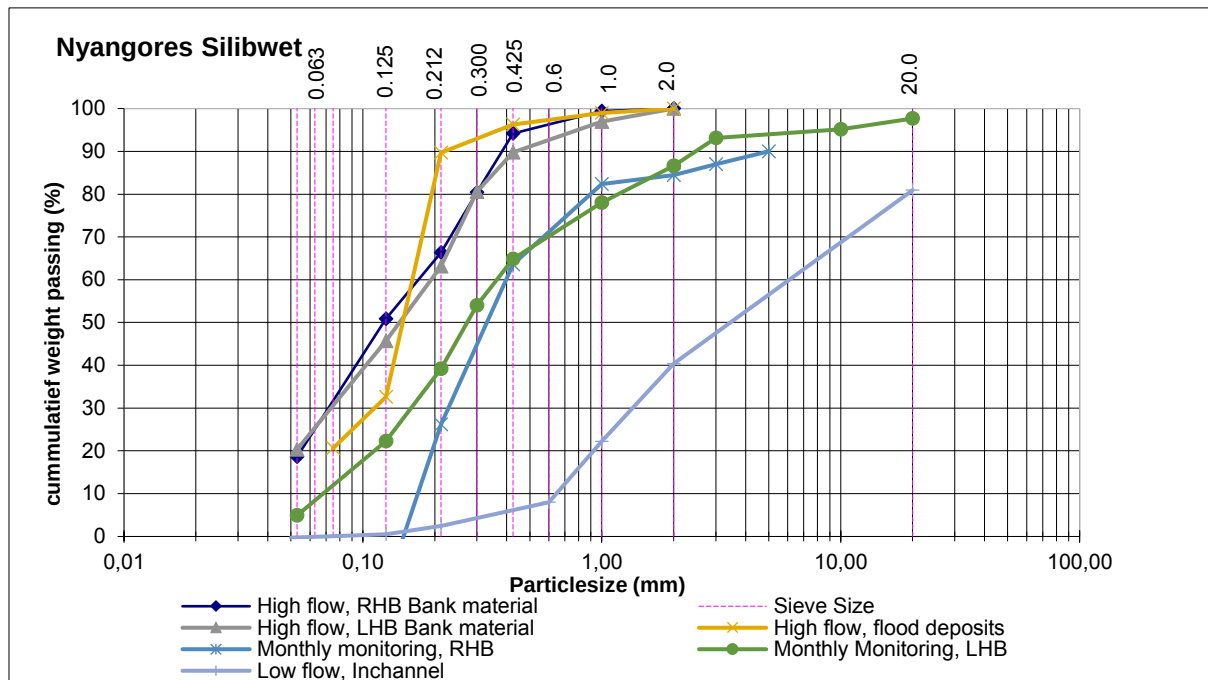
During EFA high flow survey the cross sections were surveyed with the total station. During the EFA low flow survey we also used the total station to get important points on the cross section. After that, we also started the DGPS survey. Unfortunately the receiver could not get contact of enough satellites, probably due to the canopy and hill slopes. So below, you will find the cross sections for the high flow survey only.

Cross section Nyangores Silibwet T1**Cross section Nyangores Silibwet T2****Cross section Nyangores Silibwet T3**

Sediment analysis

During the high flow survey, flood deposits on both banks were taken, together with bank material of the left and right hand bank. It was impossible to get bed sediments, since the flow was taking the grab sampler with it. During low flow survey we could wade through the water, and bed sediment clast sizes are taken. The bed sediment was mainly boulders and big cobble. Some silt depositions on the boulders could be found, but this was not enough to perform a grain size analysis.





Suspended sediment

The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature

Q (m ³ /s)	Turbidity (NTU)	SS (mg/L)	Source
29.947	48.2	40,25.2	Field measurement
7.893	31.731.4	26.67,30	Field measurement
1.777		33.2	Field measurements
0.352	18.7		Masesse, 27-28 March 2015

Nyangores Chemomul

07/12/2015 (EFA high flow)

06/03/2016 (EFA low flow)

The Chemomul bridge lies approximately .. km below the Tenwek dam. At this site two transects were surveyed. Just below the bridge, there was a riffle flow during EFA low flow survey, at this location the fish and macro invertebrates survey was performed. This site was selected to compare the results to the results for the upstream Nyangores site. In the previous EFA, the surveyed site for the Nyangores was also downstream the dam, much closer to the confluence with the Amala, so more downstream of the Chemomul site.



Discharge measurement

For the EFA high flow survey the average discharge measured was 33.7 m³/s, with a water level slope of 0.00228. For the EFA low flow survey the discharge was 2.100 m³/s with corresponding water level slope of 0.00334.

Date	Transect	Discharge (m ³ /s)	Mean velocity (m/s)	Maximum velocity (m/s)	Width (m)
07-12-2015	T1	34.047	1.172	2.49	21.891
07-12-2015	T2	33.428	1.285	2.43	17.432
06-03-2016	T2	2.218	0.322	0.81	16.711

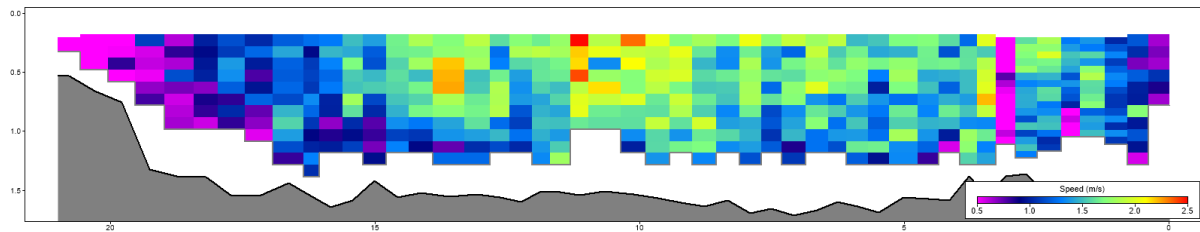


Figure 9 High flow velocity profile Nyangores Chemomul T1

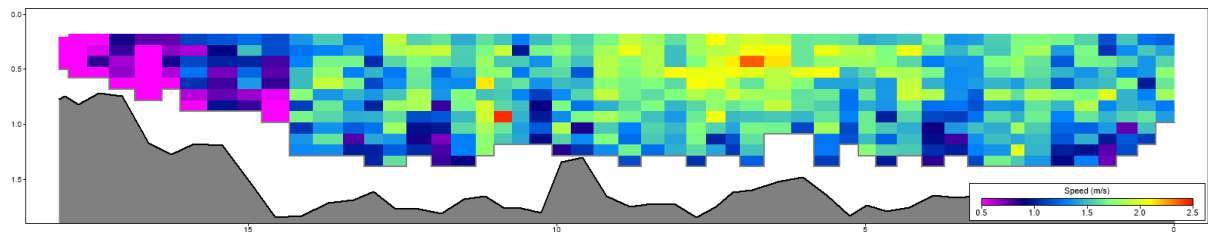


Figure 10 High flow velocity profile Nyangores Chemomul T2

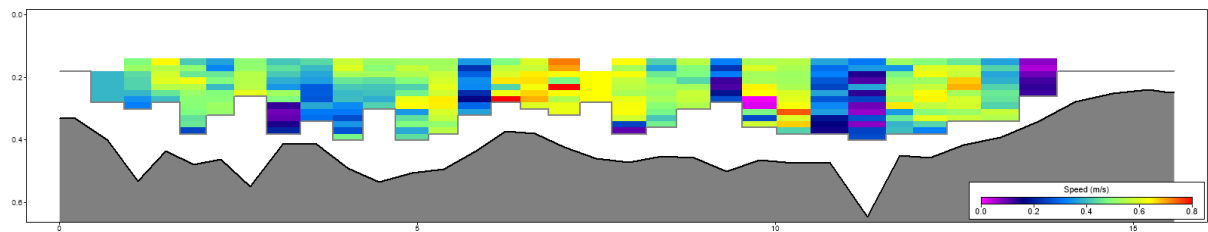
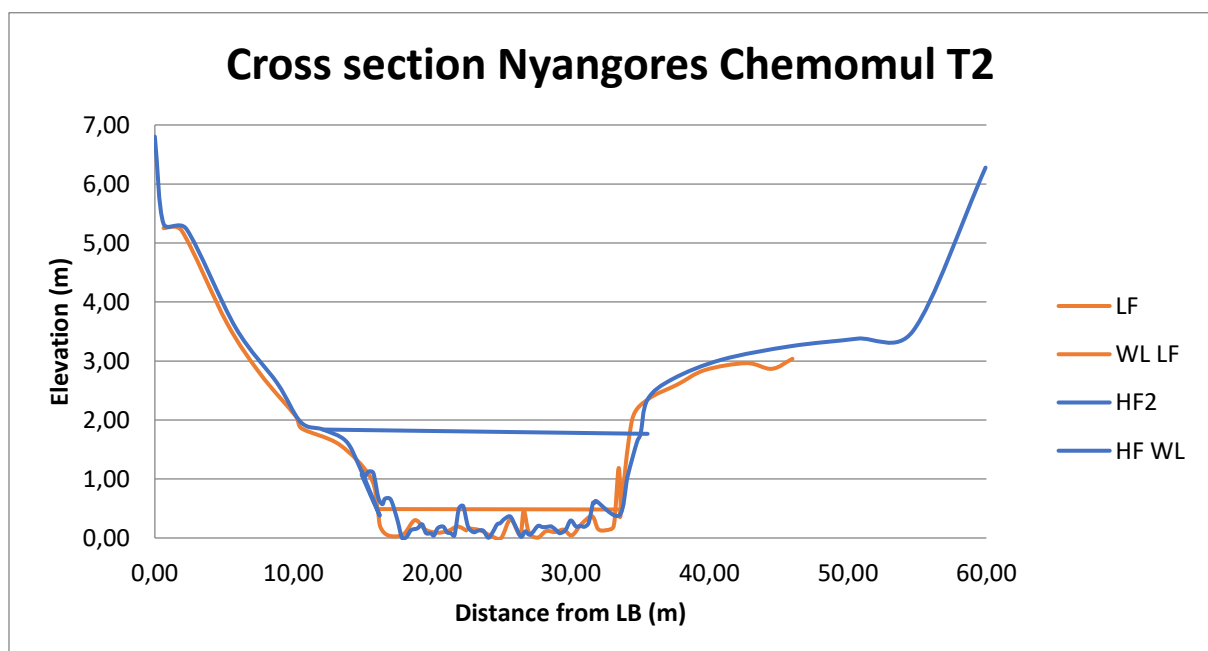


Figure 11 Low flow velocity profile Nyangores Chemomul T2

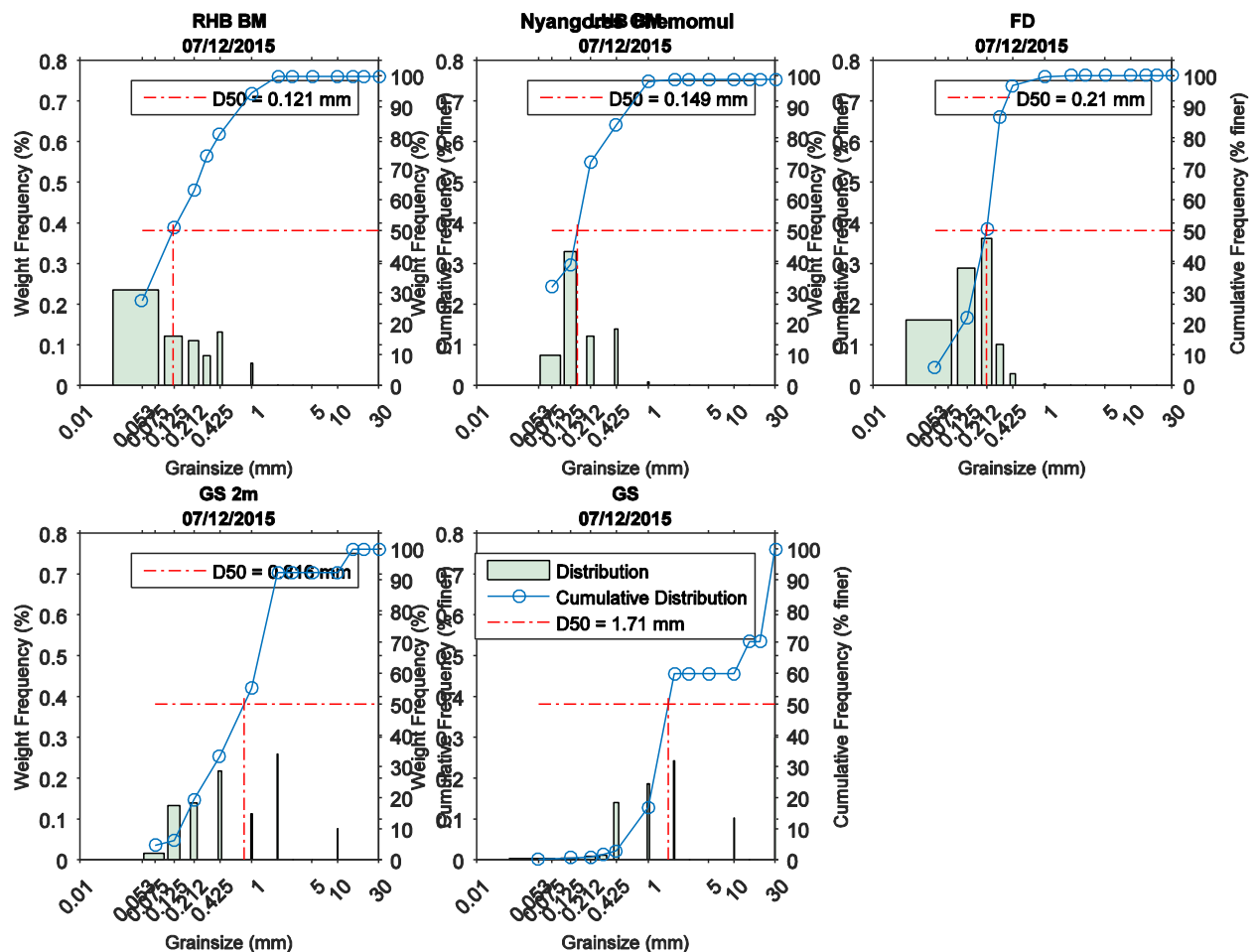
Cross sectional profile

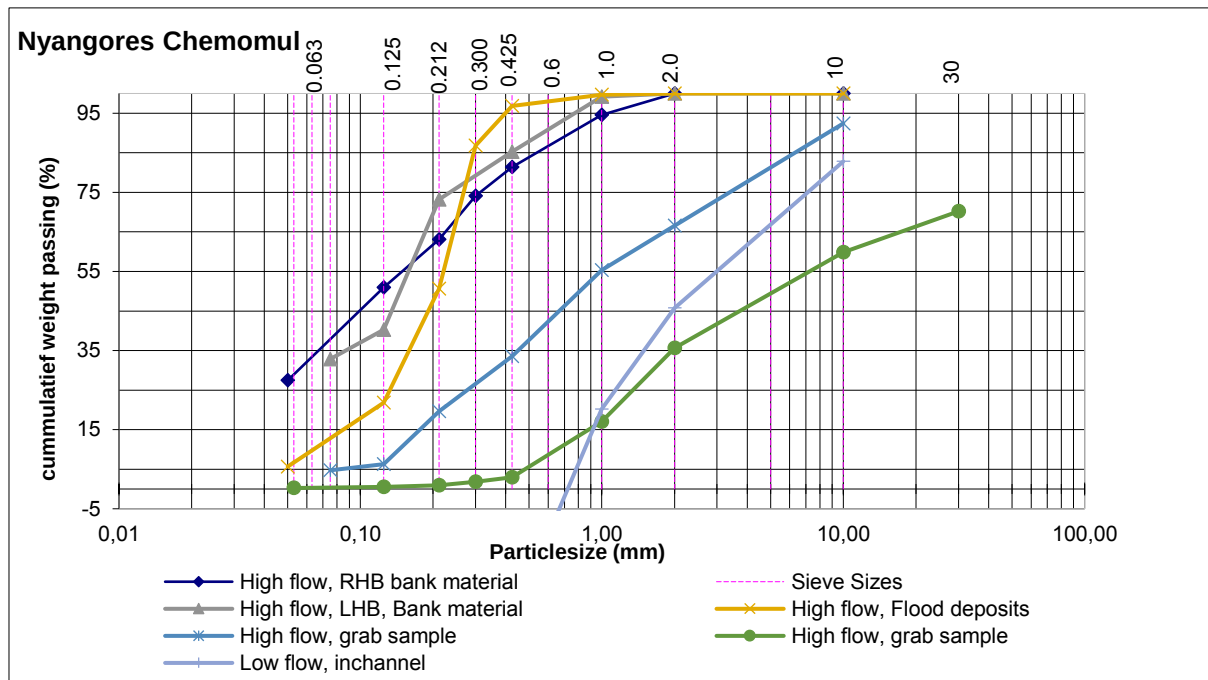
For this site, we only surveyed one cross section with a total station. This was because the forest was very dense. During EFA low flow survey, the cross section was surveyed again with a total station, because canopy was hindering the signal of satellites. The surveyed cross sections are plotted together in one graph below.



Sediment analysis

Right hand bank material, one flood deposited sample and two grab samples from the bridge are taken during the high flow survey. And during low flow EFA the bed material was measured, clast sizes of an inset flood bench downstream the bridge, and one inchannel sample was analysed on grain size. The bed material consisted mainly of boulder and cobble, with some few pockets of pebble.





Suspended sediment

The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature

Q (m ³ /s)	Turbidity (NTU)	SS (mg/L)	Source
33.7	66.6	60	Field measurement
2.1		36.4	Field measurement

Nyangores Bomet

17/12/2015 (Monthly Monitoring)

10/01/2016 (Monthly Monitoring)

The monthly monitoring along the Nyangores river takes place just at the edge of the town of Bomet, where also a gauging station is located since 1966. During the December monitoring, also with a total station the cross sectional profile and water level slope could be measured. There is a weir located at the measurement location. This weir regulates the water entering the Bomet cleaning water installation. Also, at the left bank of the river, just upstream of the bridge, cars get washed in and with river water. This is all indicated in Figure 12.



Figure 12 Planview Nyangores Bomet

Discharge measurement

The discharge was measured with the River Surveyor both in December and January. In January the water was somewhat lower, and in order to have no eddies in the profile, the measurement was done more upstream of the weir. In December we performed the measurement close to, but just upstream of the weir. The average discharge in December 49.965 m³/s, with a water level slope of measured over a length of m. In January the measured discharge was 9.094 m³/s.

Date	Gauge height (m)	Discharge (m ³ /s)	Mean velocity(m/s)	Max Velocity (m/s)	Width (m)
17-12-2015		49.019	0.977	2.0	21.5
10-01-2016	0.57	9.097	0.599	1.12	15.169

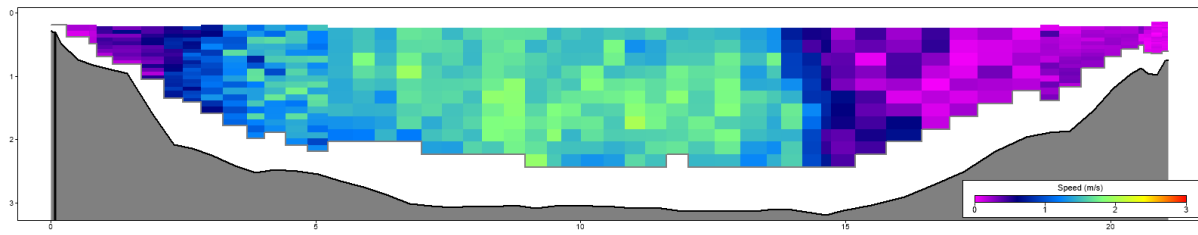


Figure 13 Flow velocity profile Monthly Monitoring December 2015

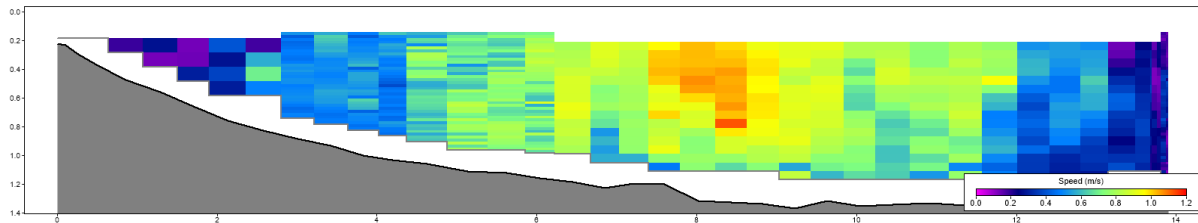
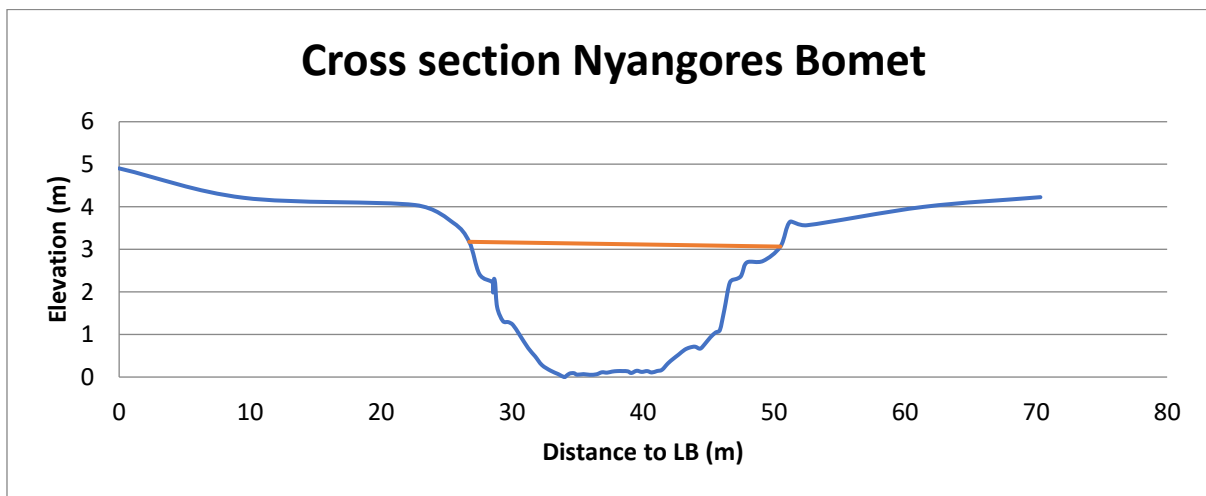


Figure 14 Flow velocity profile Monthly Monitoring January 2016 (more upstream of weir)

Cross sectional profile

The cross sectional profile was made just upstream of the weir, with a total station in combination with the river surveyor data.



Sediment analysis

In December, a bed sediment sample was collected with the grab sampler, and a flood deposit sample was collected. In January also Left hand bank deposits and right hand bank deposits were sampled. The bed material is expected to be influenced by the weir just upstream of the bridge. This will increase flow velocities downstream of the weir, and thus it is expected that coarser bed material is found there.

Suspended sediment

The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature

Q (m ³ /s)	Turbidity (NTU)	SS (mg/L)	Source
49.091	969	1650,2350 (fast flow)	Field measurement
9.097	37.5	46.67	Field measurement

Amala Kapkimolwa

08/12/2015 & 09/12/2015 (EFA high flow)

10/01/2016 (Monthly Monitoring)

08/03/2016 & 09/03/2016 (EFA low flow)

The EFA site along the Amala is equivalent to the site of the previous EFA, which is near the gauging station at Kapkimolwa bridge. The site is surrounded by smallholder farmers, some 16 kilometers away from the Mau Forest (more upstream). The police station is located upstream of the Kapkimolwa bridge. The monthly monitoring site is just upstream of the bridge, and the EFA site is approximately 140 m upstream of the bridge. At this location, on the right hand bank there are some agricultural practises in the riparian area, as can be seen in Figure 15, along this section the right hand bank shows signs of degradation/erosion. During both EFA surveys three cross sections were surveyed at the EFA site. Also during the low flow EFA survey the gauging station cross section was surveyed. During the EFA low flow survey both total station and DGPS were used, to ensure that we had good signal with the DGPS.



Figure 15 Planview Amala Kapkimolwa site

Discharge measurement

All discharges measured were accomplished with the River Surveyor. During high flow survey, we had to come back the next day to finish the measurement, because of a problem with the battery. Transect 1 was located in a pool area, just before a rapid, transect 2 was through a riffle, and transect 3 along a pool area again.

Date	Survey	Gauge height (m)	Discharge (m ³ /s)	Slope (m/m)	Distance for slope measurement (m)
08-12-2015	EFA high flows		22.487	0.004954	85
09-12-2015	EFA high flows/MM		20.0925	-	-
10-01-2016	Monthly monitor.	0.54	3.833	-	-
08-03-2016	EFA low flows		1.148		

Date	Transect	Discharge (m ³ /s)	Mean velocity (m/s)	Maximum velocity (m/s)	Width (m)
08-12-2015	T1	23.302	1.465	2.82	13.878
08-12-2015	T2	24.769	1.340	2.73	16.811
09-12-2015	T3	19.970	1.008	2.54	14.789
09-12-2015	Gauging station	20.413	1.406	2.94	12.614
10-01-2016	Gauging station	3.896	0.679	1.08	8.160
08-03-2016	T1	1.263	0.269	0.81	10.791
08-03-2016	T2	1.163	0.275	0.97	9.38
08-03-2016	T3	1.034	0.124	0.69	13.224

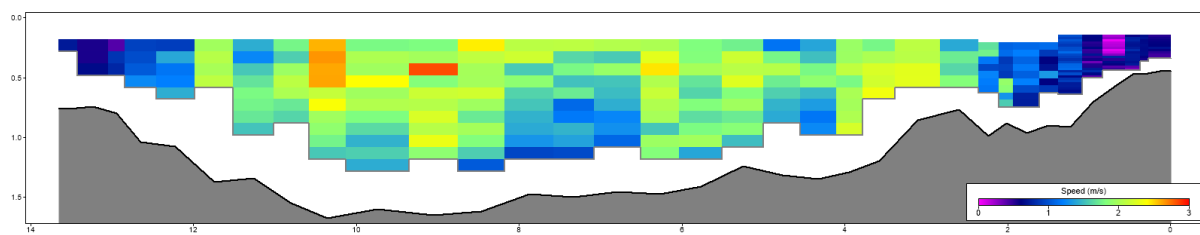


Figure 16 High flow velocity profile Amala Kapkimolwa T1 (08-12-2015)

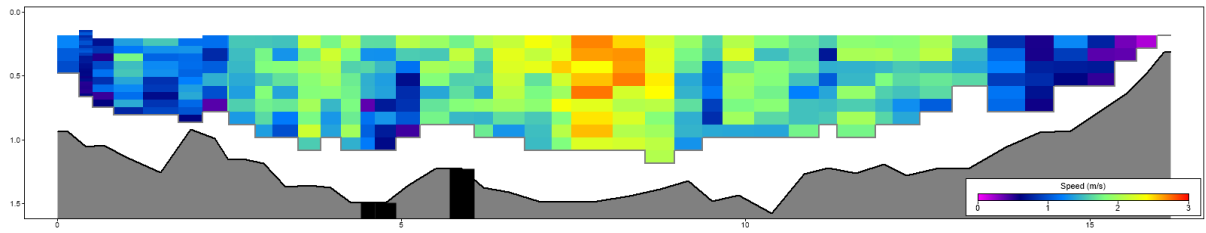


Figure 17 High flow velocity profile Amala Kapkimolwa T2 (08-12-2015)

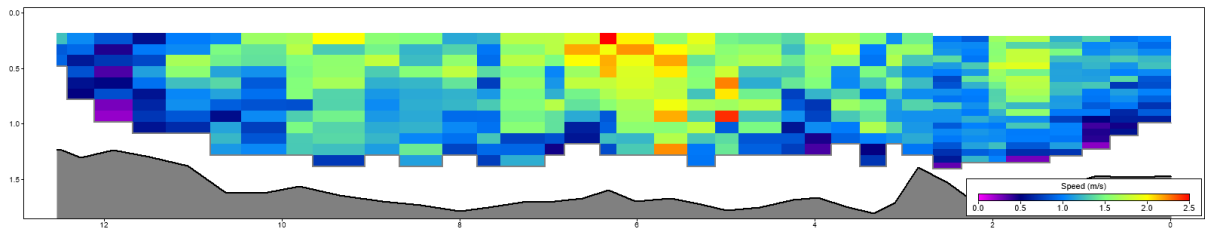


Figure 18 High flow velocity profile Amala Kapkimolwa T3 (09-12-2015)

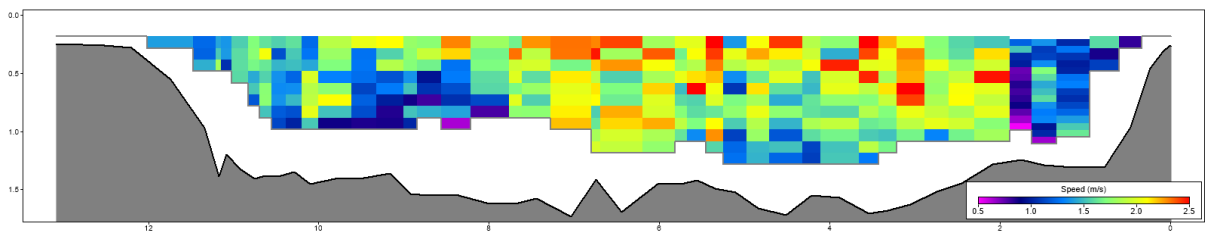


Figure 19 Flow velocity profile Amala Kapkimolwa Gauging station December 2015

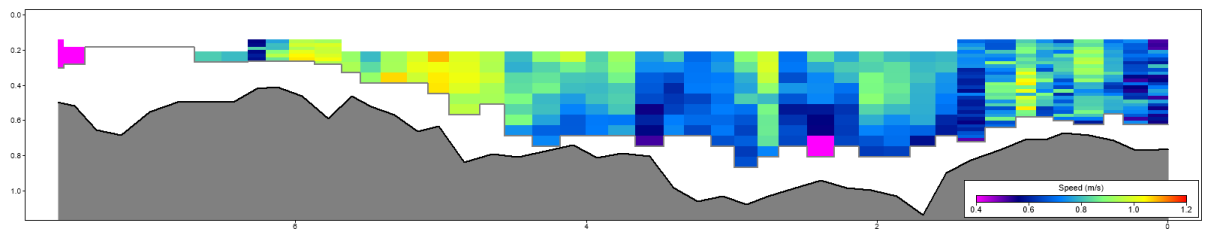


Figure 20 Flow velocity profile Amala Kapkimolwa Gauging station January 2016

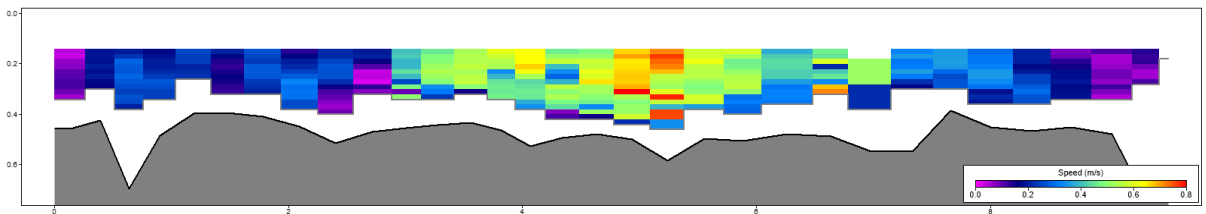


Figure 21 Low flow velocity profile Amala Kapkimolwa T1

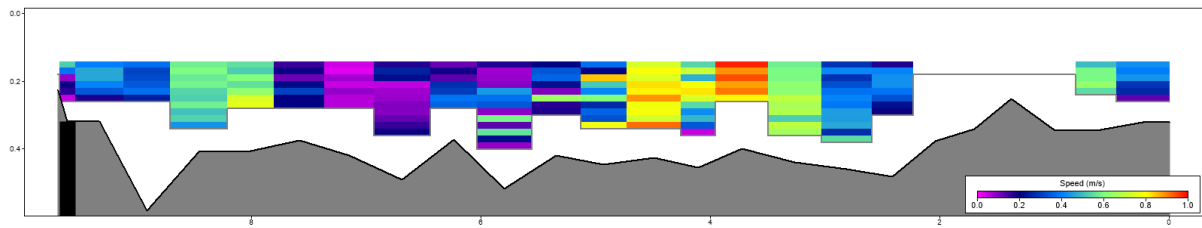


Figure 22 Low flow velocity profile Amala Kapkimolwa T2

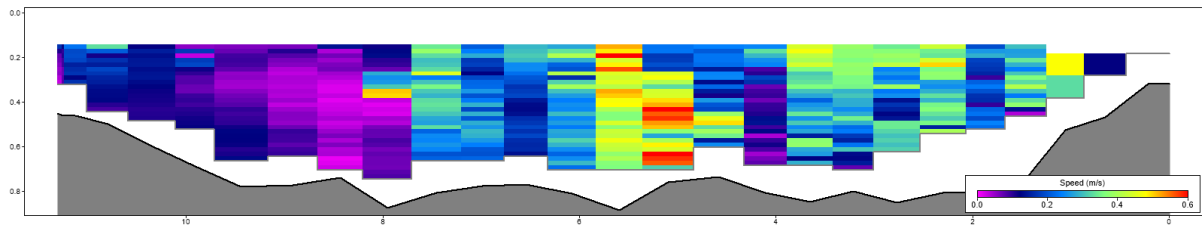
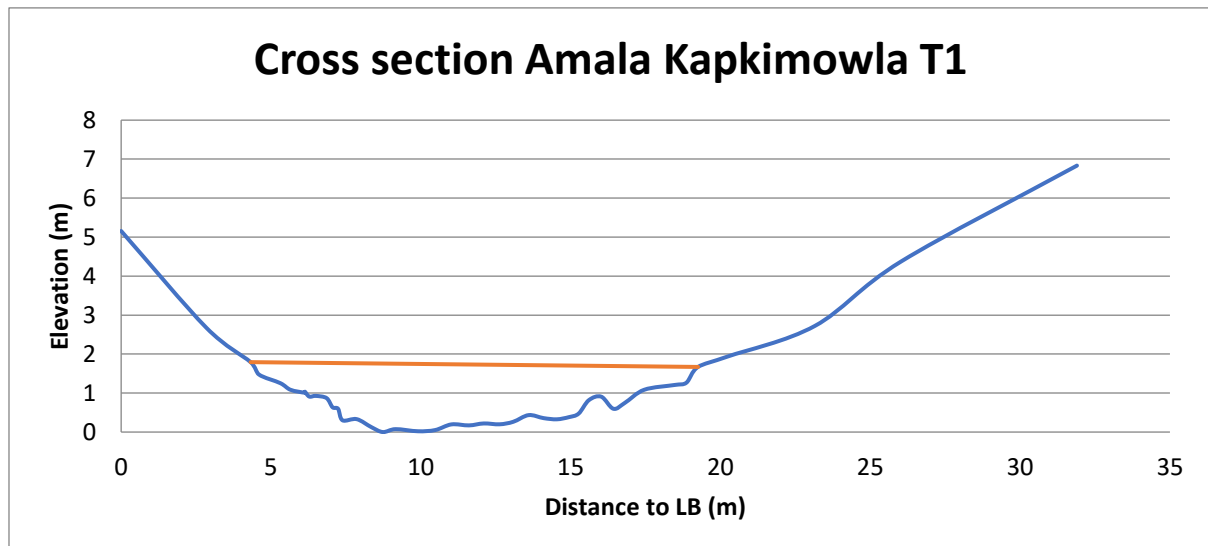


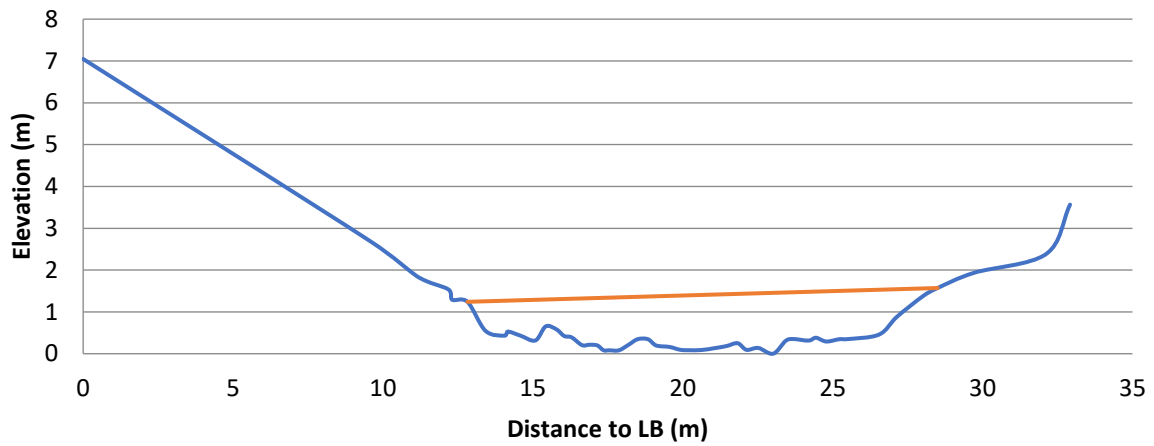
Figure 23 Low flow velocity profile Amala Kapkimolwa T3

Cross sectional profile

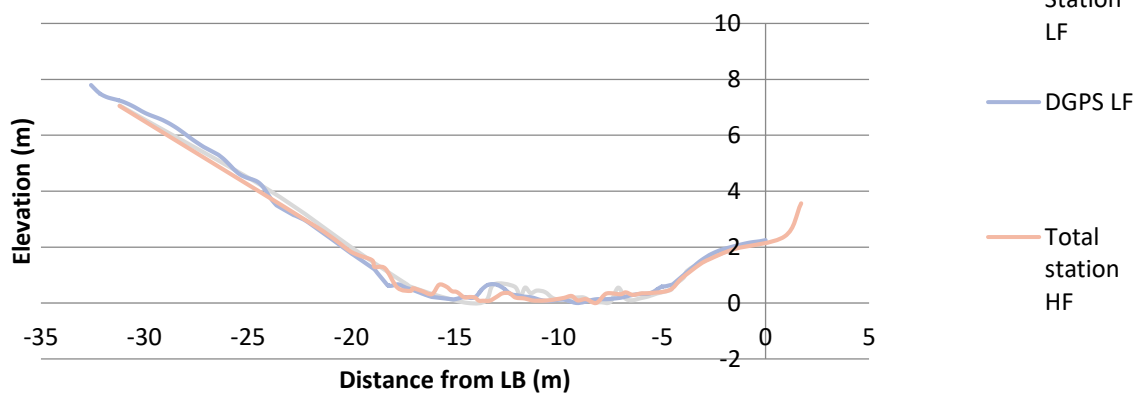
During EFA high flows the cross sections was established by combining the River Surveyor data with the Total station data for the wet and dry cross section respectively. It was not possible to wade through the water because the flow velocity in combination with the depth was too high ($>1\text{m/s}$ and depth $>1\text{m}$). During the EFA low flow survey, the cross sections were initially measured with the total station, considering that the previous days the signal the DGPS received was not good enough to estimate accurately the position. Then, one day after, at 09-03-2016, I went back to get data with the DGPS, in order to have it, and compare the elevation with other sites. Results from the DGPS, and total station high and low flow EFA can be seen below. The other cross sections I did not process yet for the DGPS.



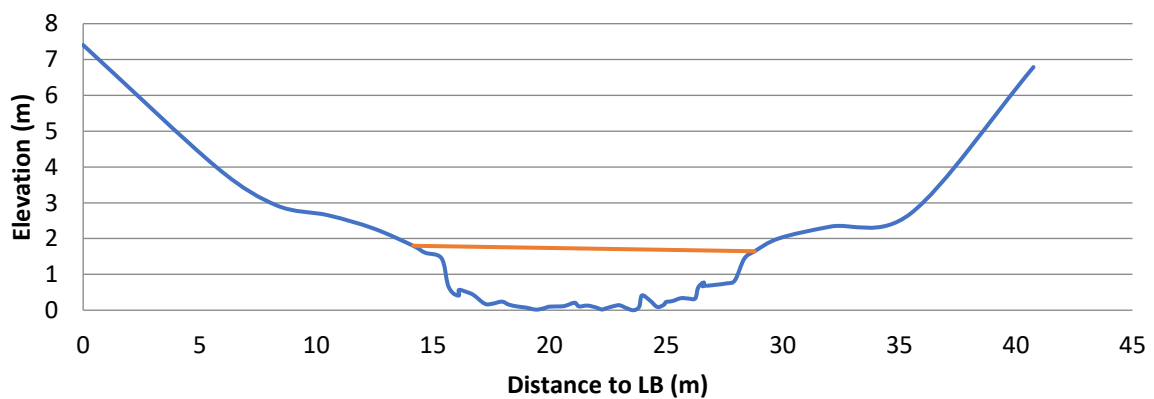
Cross section Amala Kapkimolwa T2



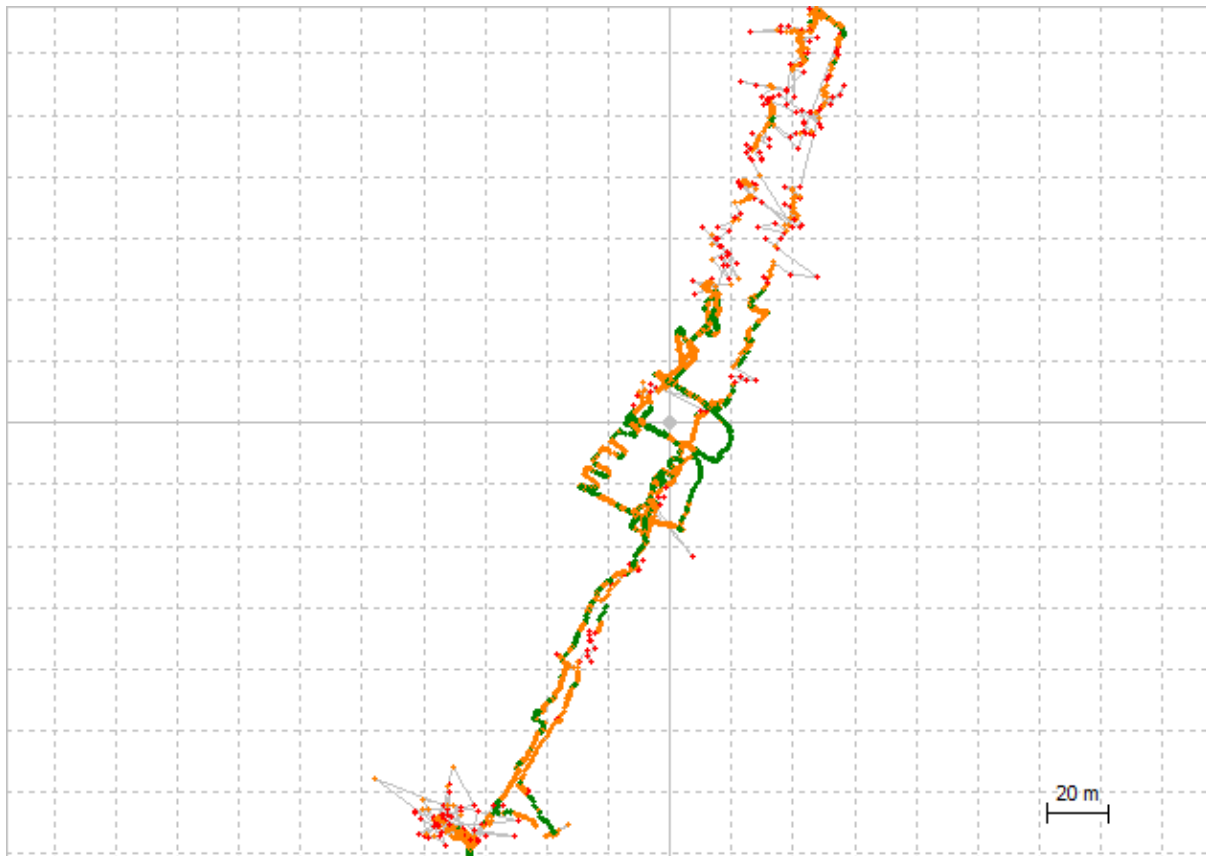
Cross section Amala Kapkimolwa T2



Cross section Amala Kapkimolwa T3



Differential GPS geometry



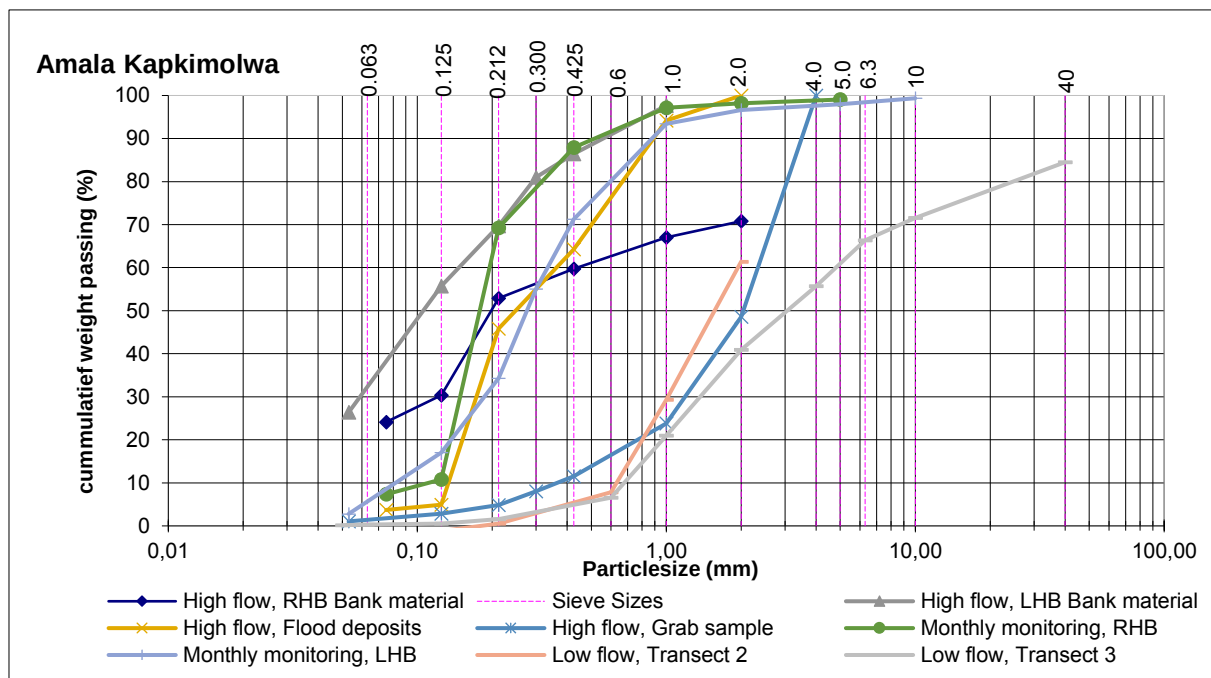
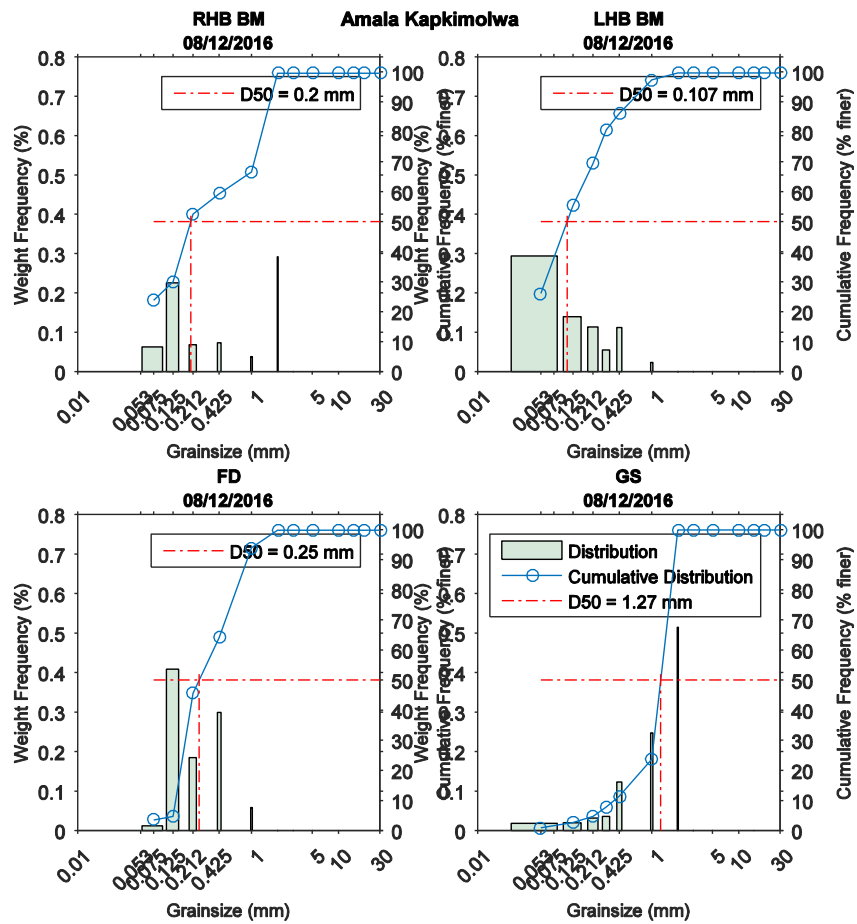
Sediment analysis

During EFA high flow survey flood deposits were sampled, and a grab sample was taken from a pool, and bank material from both banks was sampled. During EFA low flow survey the bed could be sampled appropriately. As expected, there were parts which were bedrock confined, with boulders and some pockets of gravel and sand. In the pool transect, gravel and sand was found. There were 3 samples made for grain size analysis; for each transect one. Next to that along the transects clast sizes were measured.

Suspended sediment

The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature

Q (m ³ /s)	Turbidity (NTU)	SS (mg/L)	Source
22.487	84.6	120	Field measurement
3.833	38.6	20	Field measurement
1.148		49.6	Field measurements
0.1	25.7		Masese, 27-28 March 2015



Talek Olare Orok

03/12/2015 (EFA high flow)

03/03/2016 (EFA low flow)

The Talek Olare Orok site is just downstream of the confluence of the Lemek and Talek rivers. The site is located in the Massai Mara. Just after the confluence a bedrock feature was found, just upstream of the bedrock control there is a big hippo pool. Downstream of the bedrock there is a pool again. Further downstream this sequence repeats itself. During low flows, the faeces of the hippos could be seen everywhere at the bedrock, and we found a lot in the grab samples as well. Discharge measurements were done with the River Surveyor and the Flow tracker for three cross sections. During EFA low flow survey, also a detailed description of 4 transects on the bedrock was made to describe the fish habitat there.



Discharge measurement

During both the EFA high and low flow survey, the upper transect, along the rapid was measured with the Flow Tracker, and the other two transects were measured with the River Surveyor.

The water level slope measured during EFA high flow was 0.01172 m/m over a total distance of 120 m. This can be divided into a pool section (downstream – T2) where the slope was 0.00011876m/m, and a riffle section where the slope was 0.03162m/m.

During EFA low flow survey, the water level slope was divided in a pool part, and in a riffle part. The slope over the riffle was 0.255 m/m measured over 58m. The slope over the pool part was 0.0006265m/m measured over 94m. The overall slope (adding these two up) is 0.010138m/m measured over 152m.

Date		Discharge (m ³ /s)	Mean velocity (m/s)	Maximum velocity (m/s)	Width (m)
12/03/2015	FT T1	1.41	0.328	1.395	26
12/03/2015	RS T2	3.733	0.184	0.73	26.3
12/03/2015	RS T3	3.520	0.181	0.71	27.6
03/03/2016	FT				
03/03/2016	RS T2	0.099	0.014	0.25	15.804
03/03/2016	RS T3	0.200	0.017	0.08	20.9

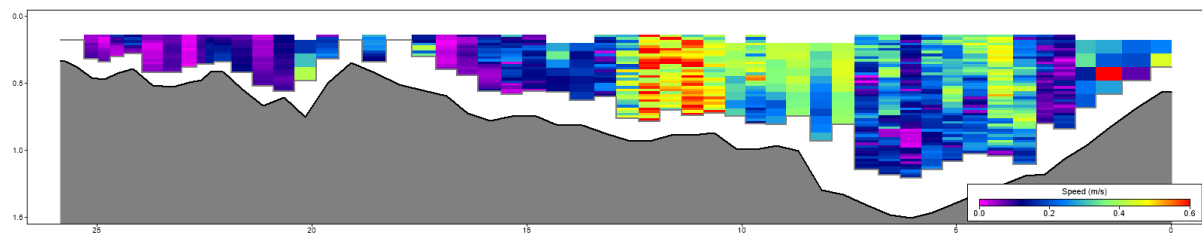


Figure 24 High flow velocity profile Talek Olare Orok T2

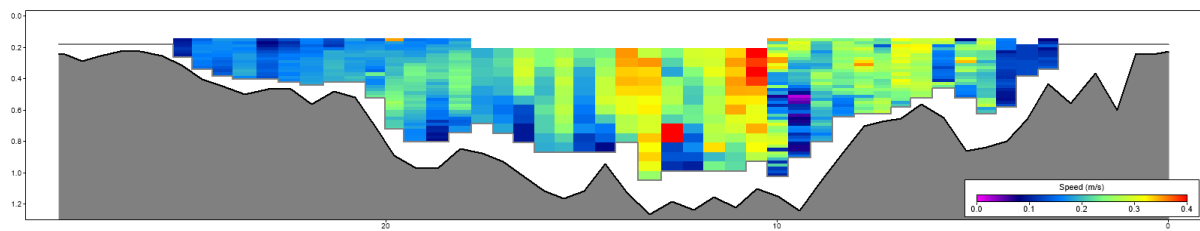


Figure 25 High flow velocity profile Talek Olare Orok T3

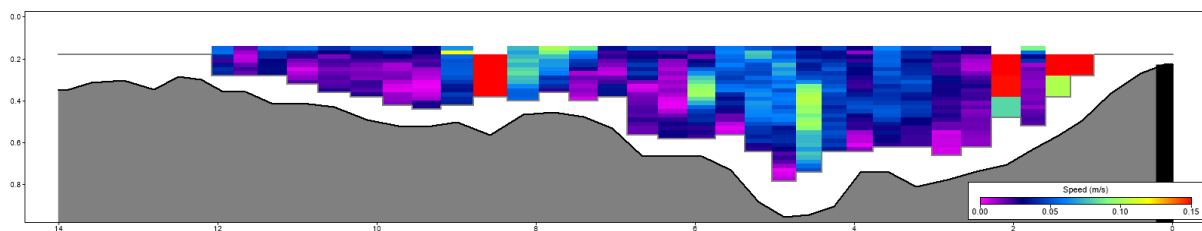


Figure 26 Low flow velocity profile Talek Olare Orok T2

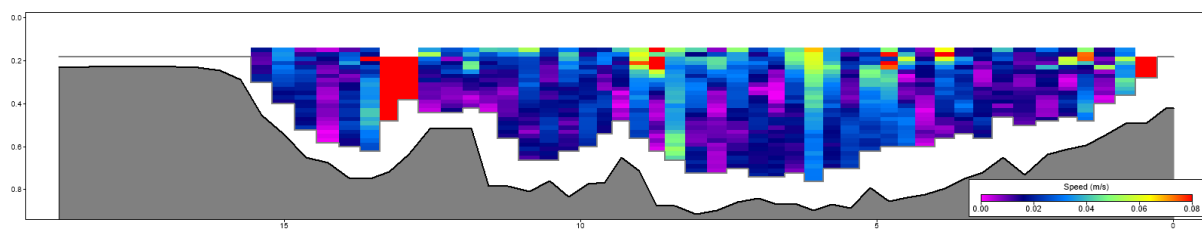
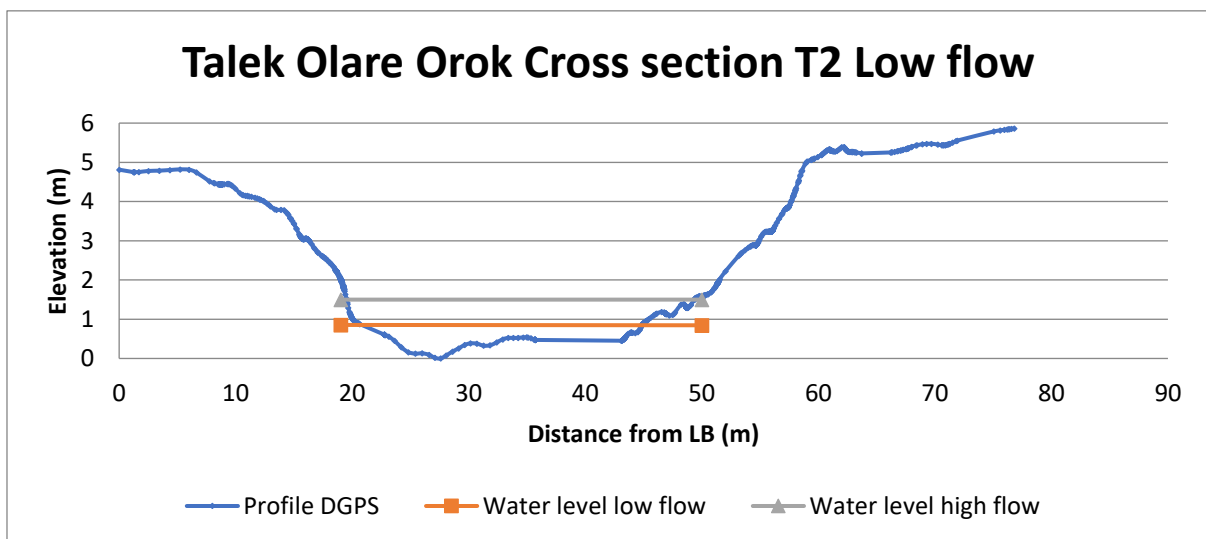
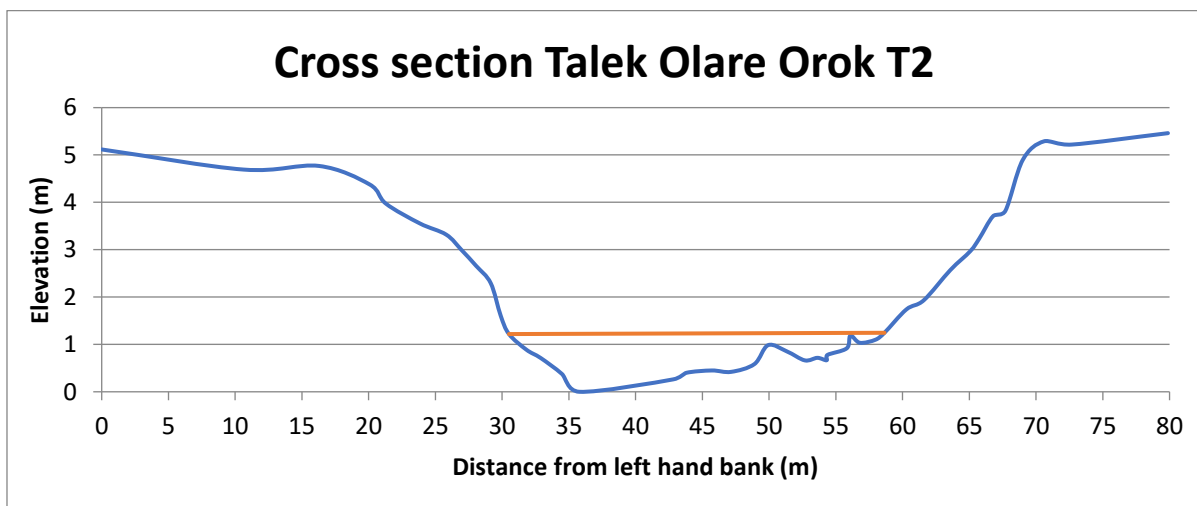
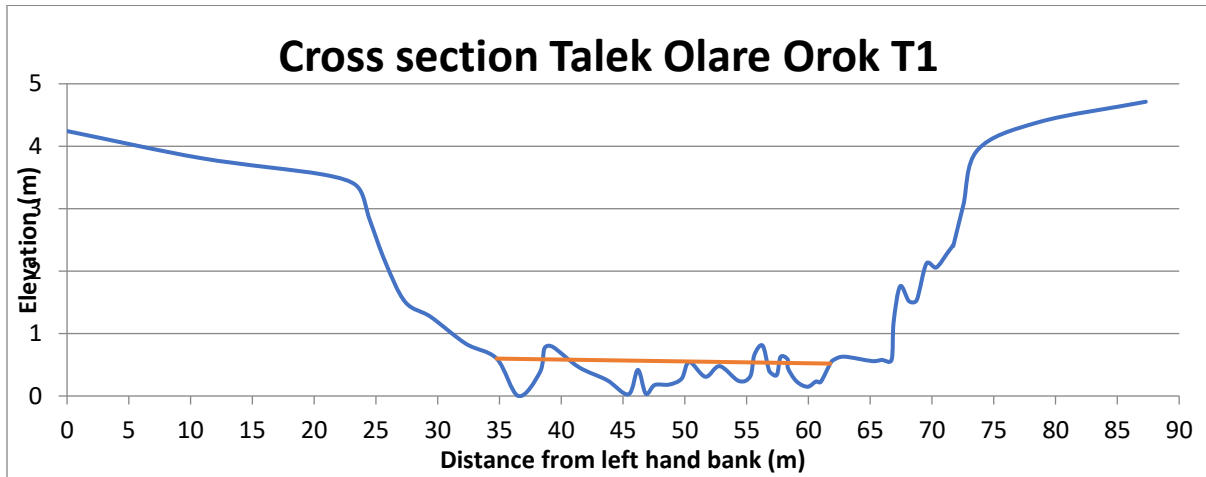


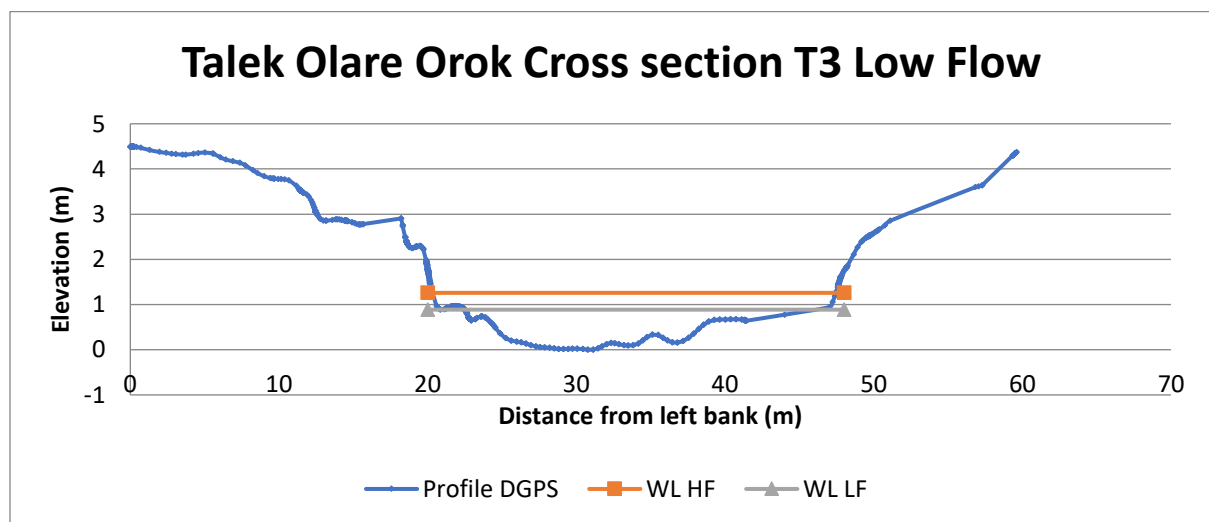
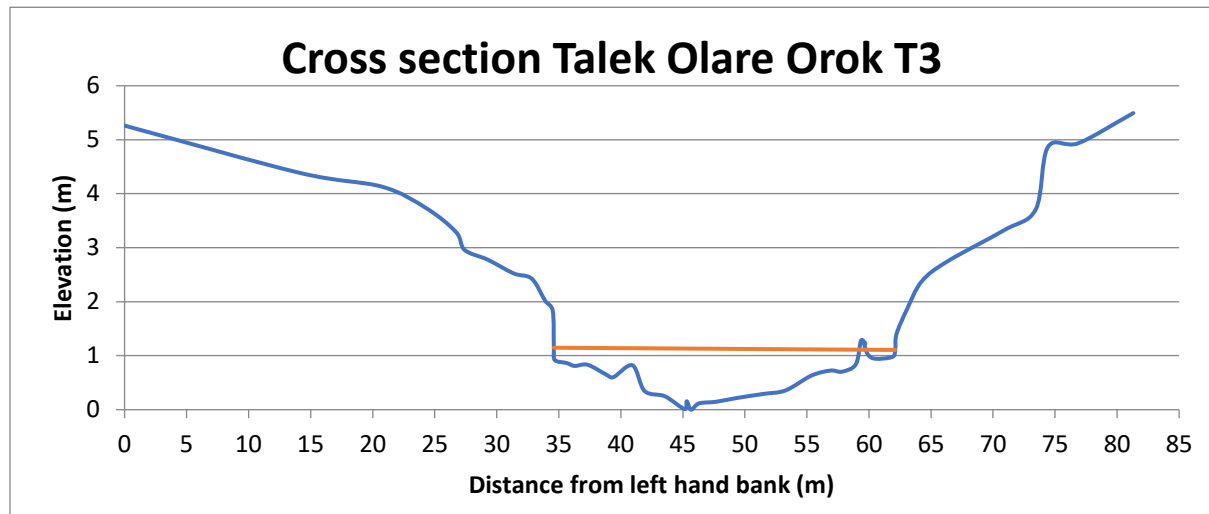
Figure 27 Low flow velocity profile Talek Olare Orok T3

Cross sections

For the EFA high flow survey the cross section was measured fully with the Total Station. For the EFA low flow survey the cross sections were measured with the DGPS, combined with the River Surveyor for T2 and T3.



Different run of RS used for velocity-depth data (no7) than to fit into the cross sectional profile (no 8).



Differential GPS geometry

Sediment analysis

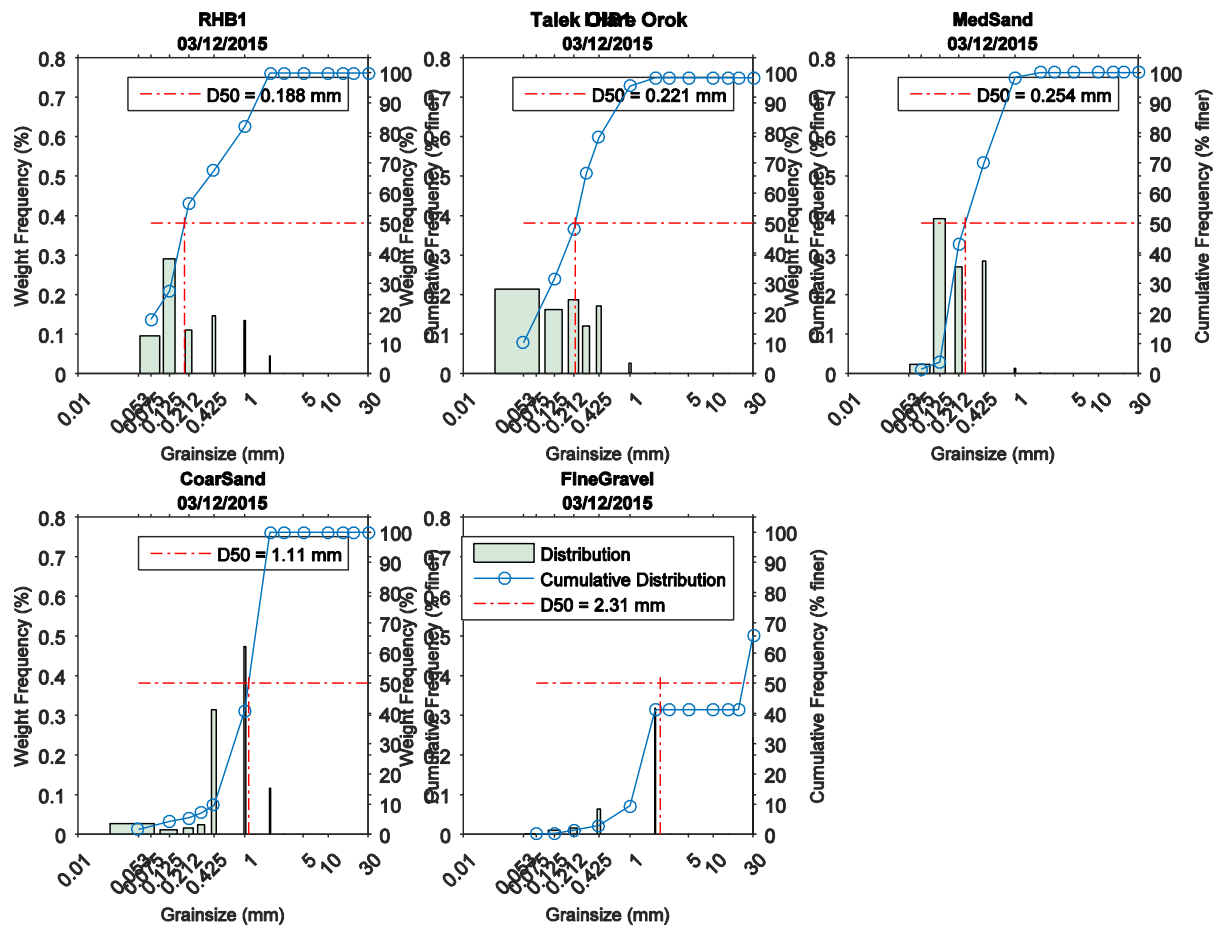
Just after the confluence a bedrock control is present, and at the banks on this location 100 pebbles were count for grain size analysis. In the pool area, after the bedrock, different sizes of sand were sampled during EFA high flow survey by diving into the water. These are displayed below. During the EFA low flow survey sediment samples were taken from the pool area with a grab sampler. In these samples a lot of hippo shit was found. Next to that, also samples from near the water edge were taken for both left and right bank.

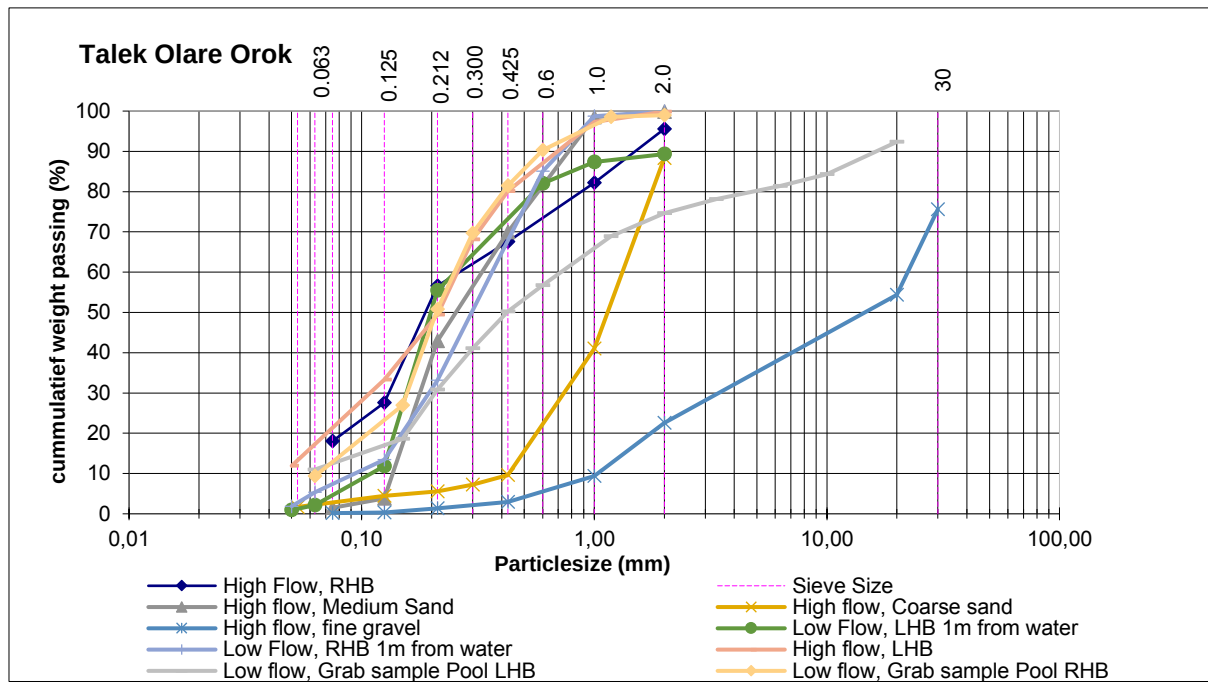
Suspended sediment

The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature.

Q (m3/s)	Turbidity (NTU)	SS (mg/L)	Source
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3.6	382	300,430	Field measurement
0.1		138	Field measurement





Talek Gauging Station

07/01/2016 & 27/01/2016 (Monthly Monitoring)

The Talek gauging station is located upstream of the park, in Talek town, at the bridge. The gauging station is installed in 2012. The hydrology of the Talek catchment is very flashy though, so flows are usually low, with some short flood events. The gauging plate is attached to the bridge, where the bed is very rocky, and water flows over the whole width between rocks. Below the bridge there is a sandy section, where the river flow is more confined which is a good place to measure the discharge. In December this was done with the Flow Tracker, and in January the cross section at the bridge was measured, and the discharge downstream of the bridge was measured with the River Surveyor.

Discharge measurement

Date	Gauge height (m)	Discharge (m ³ /s)	Max velocity (m/s)	Mean velocity (m/s)	Width (m)	Slope (m/m)
07-01-2016	0.40	0.288	0.471	0.357	6.75	-
27-01-2016	??	1.896	0.67	0.247	16.55	0.00991 (224m)

On the 7th of January the discharge measured was 0.288 m³/s, and the width was 5.6 m, depth 0.15m, with average flow velocity of 0.808 m/s. On the 27th of January the discharge was 1.896 m³/s, with a width of 15.39m depth of 0.4m and the slope of the water level was 0.00991 m/m measured over a distance of 224m.

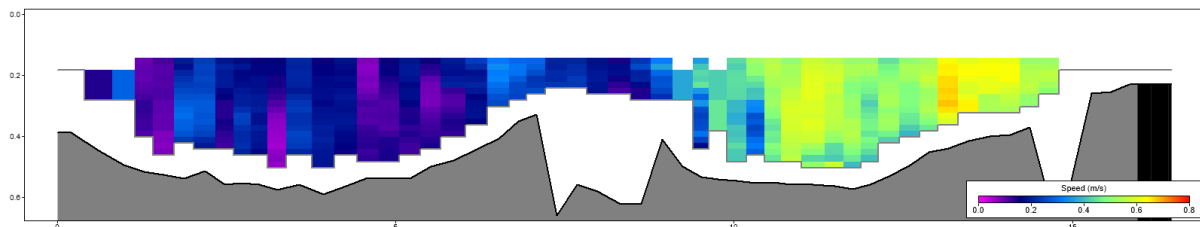
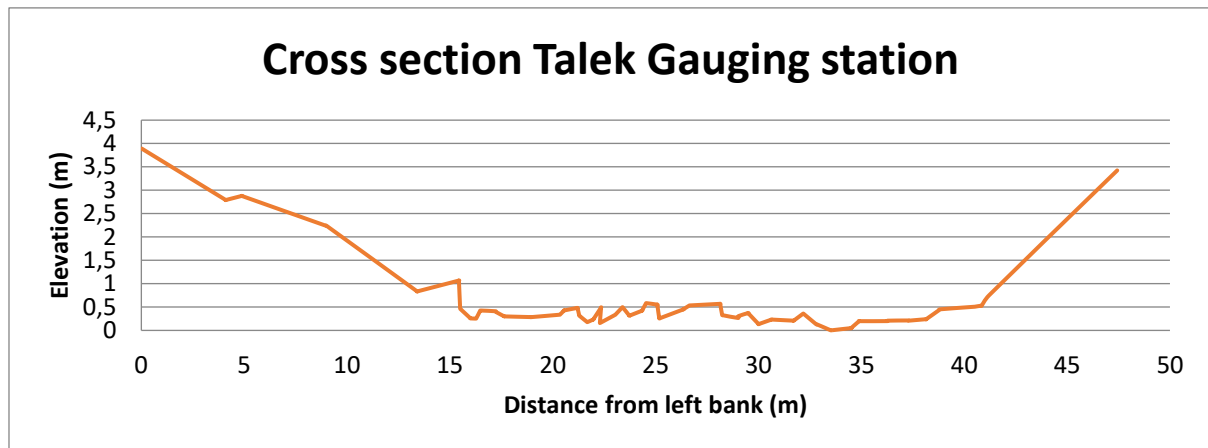


Figure 28 Flow velocity profile Talek gauging station, 50 m downstream bridge January 27th 2016

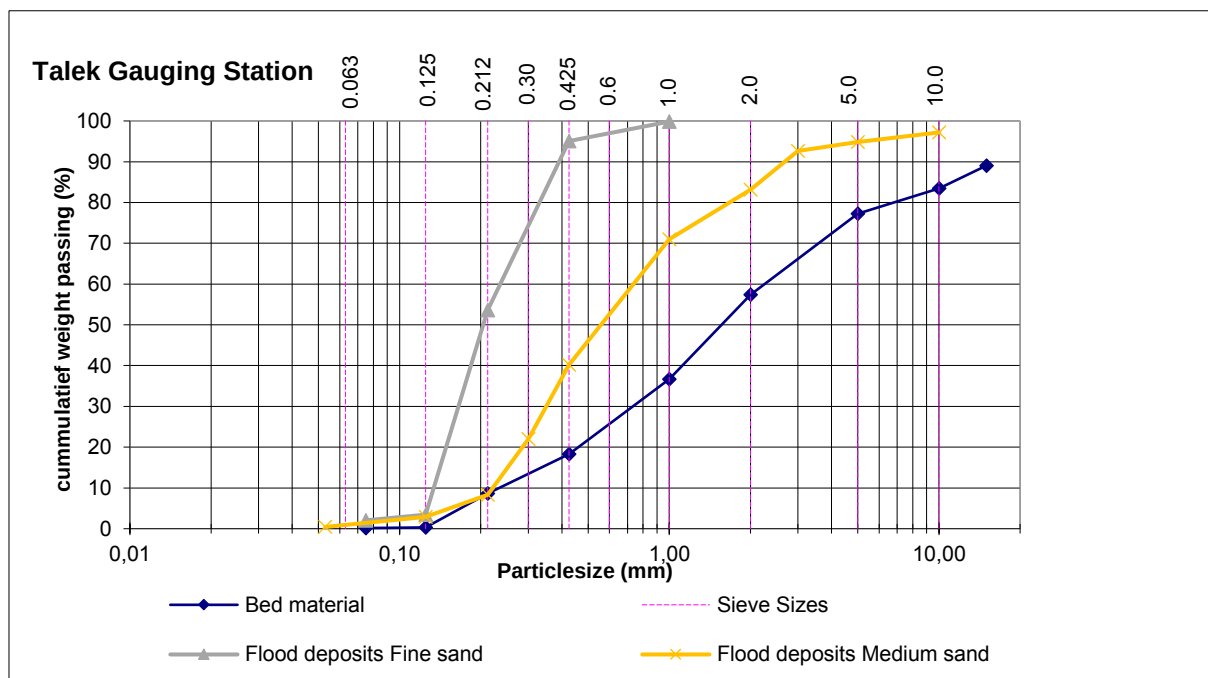
Cross sectional profile

The cross sectional profile was made with a total station, 5m upstream of the bridge. With this cross section, it was hoped to make a rating curve for the site, but unfortunately there are insufficient measurements of discharge together with gauge height, which are needed to make the rating curve.



Sediment analysis

There are many different habitats near the Talek gauging station. Upstream and downstream of the bridge ($\pm 10\text{m}$ on both sides) there are a lot of boulders together with islands of bigger pebbles found. Also an instream vegetated flood bench with shrubs is located downstream on the left side of the channel. Over these boulders there is a small rapid visible at the downstream side of the bridge. After these 10m the bed material gets finer and finer, and the part where we did the measurement of the discharge, there is a lot of sand, with big sand deposition bench on the right bank before the river bends. The left hand bank is more vegetated, and the right hand bank more sand with one patch of shrub and grass. On the upstream side of the bridge there are patchy vegetated islands of bedrock. A mixed sample of bed sediments was collected, together with a sample of deposited sand.



Suspended sediments

The turbidity with a discharge of $0.288 \text{ m}^3/\text{s}$ was 71.6 NTU, and a TSS of 50 mg/L

Sand River

02/12/2015 (EFA high flow)

08/01/2016 (Monthly monitoring)

02/03/2016 (EFA low flow)

The site at the Sand river is located near the border with Tanzania, and 50 km upstream of the confluence with the Mara River. The flows in the Sand are naturally very flashy, and the river consists of coarse sand mainly. During the EFA high flow survey we were able to measure some flows upstream of the bridge. Downstream of the bridge the river is very patchy vegetated with fast flowing streams between these vegetated islands/rocks, this is also where the most fish and macro invertebrates were found. During the monthly monitoring and the EFA low flow survey there was not enough water in the river to measure the discharge, even the floating method did not work.

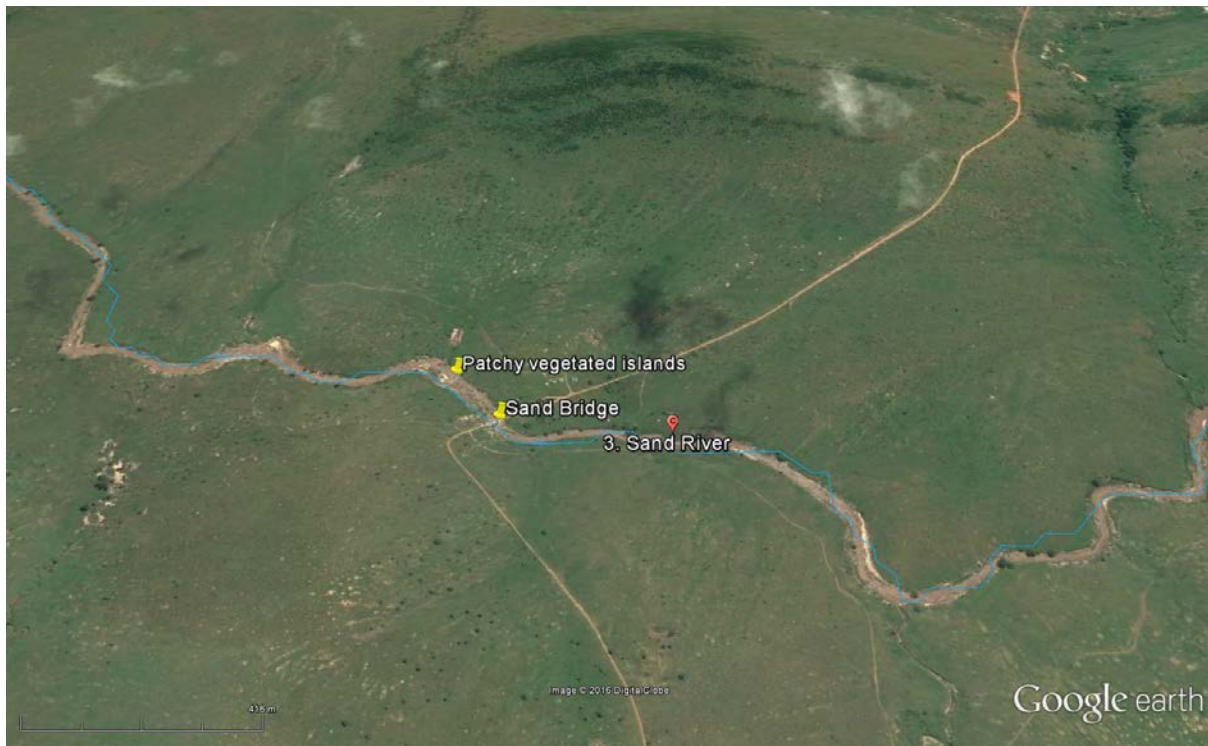


Figure 29 Site overview Sand river

Discharge measurement

Discharge measurements during EFA high flow survey were performed with the Flow Tracker, which measures the flow velocity, and the discharge was calculated with the velocity-area method.

Transect	Gauge height (m)	Discharge (m ³ /s)	Mean velocity (m/s)	Maximum velocity (m/s)	Width (m)
1	0.3	0.677	0.248	0.469	19.0

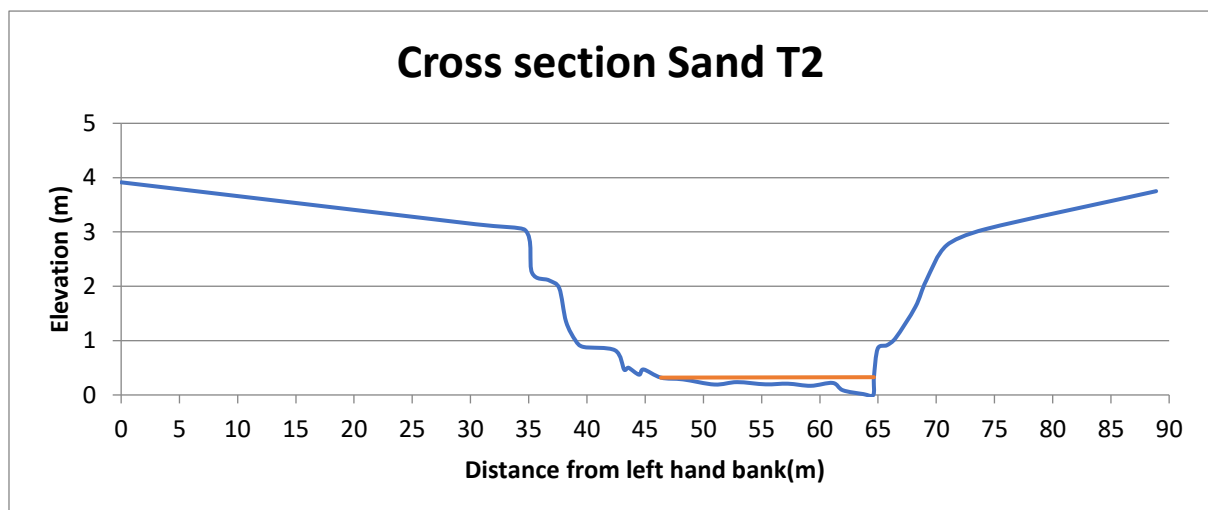
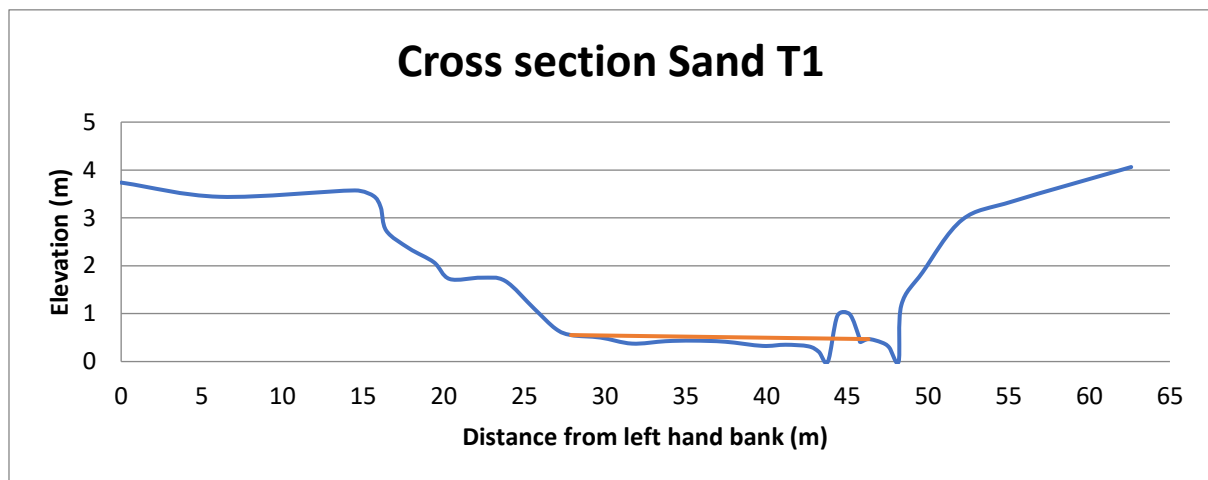
2		0.842	0.325	0.84	18.5
3	0.25	0.651	0.181	0.537	28.6

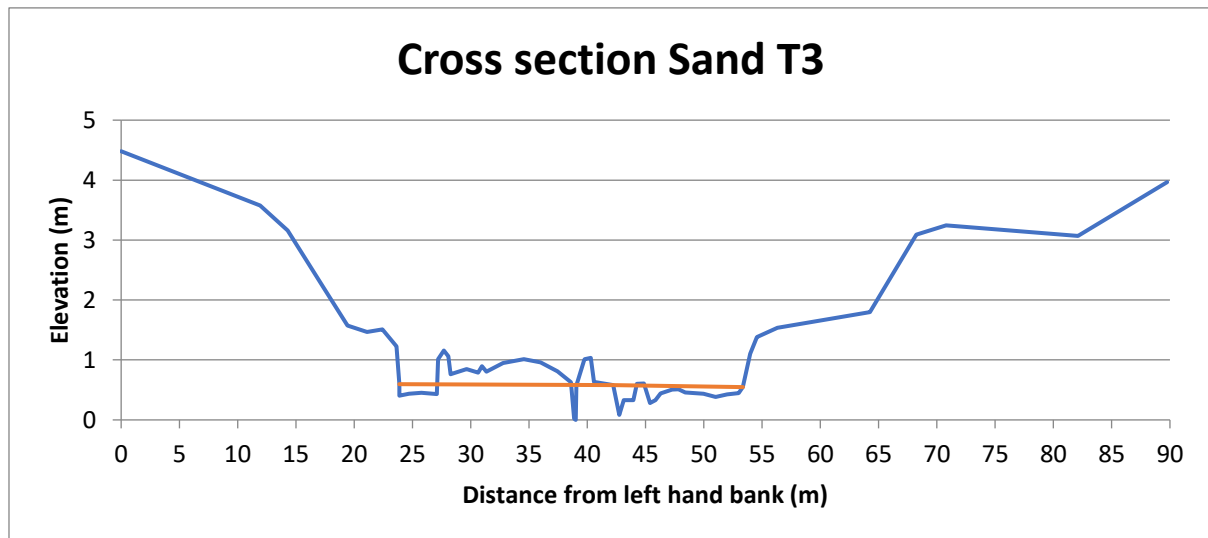
The average discharge was 0.6 m³/s.

The water level slope was measured over a distance of 165.3 m and the height difference was 0.498 m so the slope during this flow event was 0.00301 m/m.

Cross sectional profile

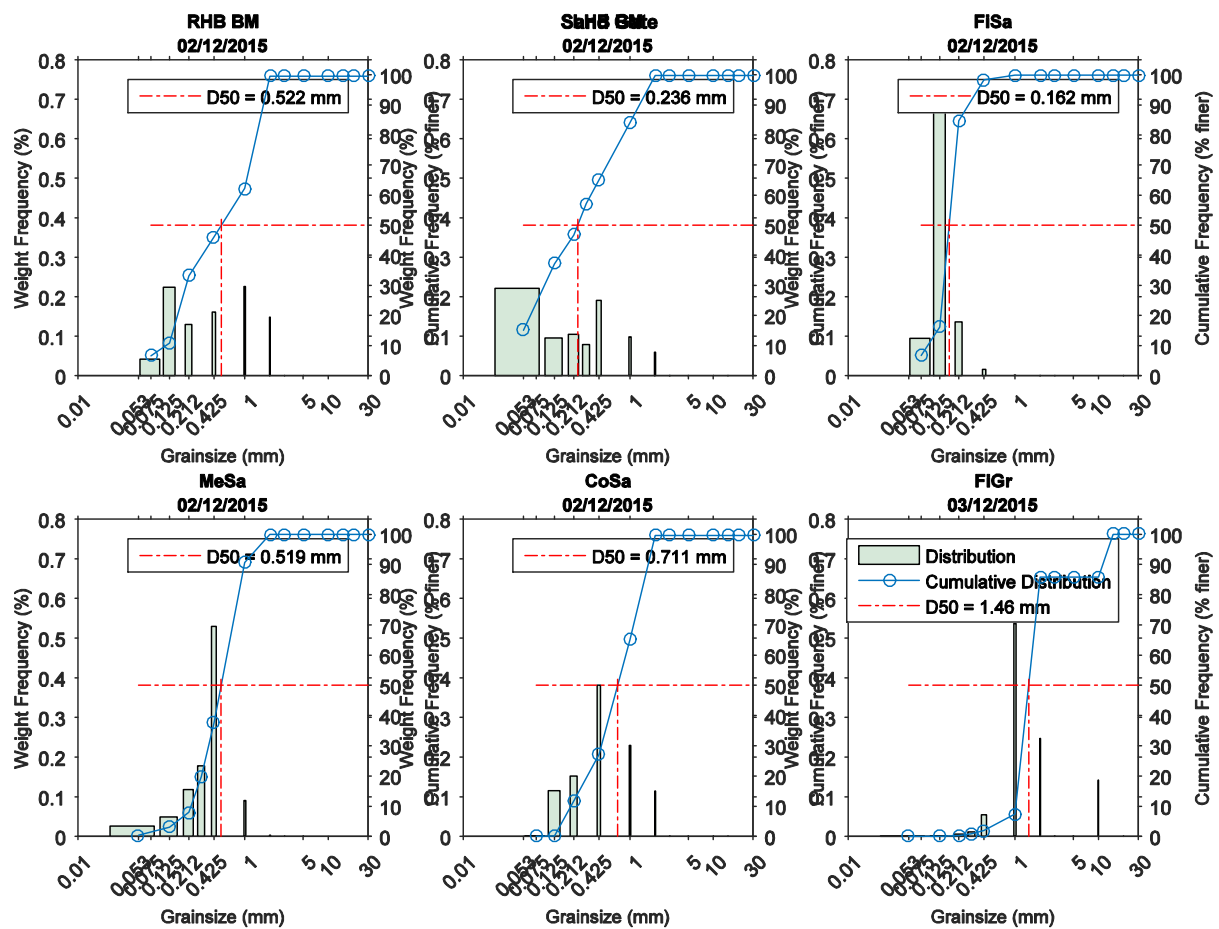
This was measured during EFA high flow survey with the Total station fully. During the EFA low flow survey, unfortunately the DGPS was not receiving any data to make accurate position files.

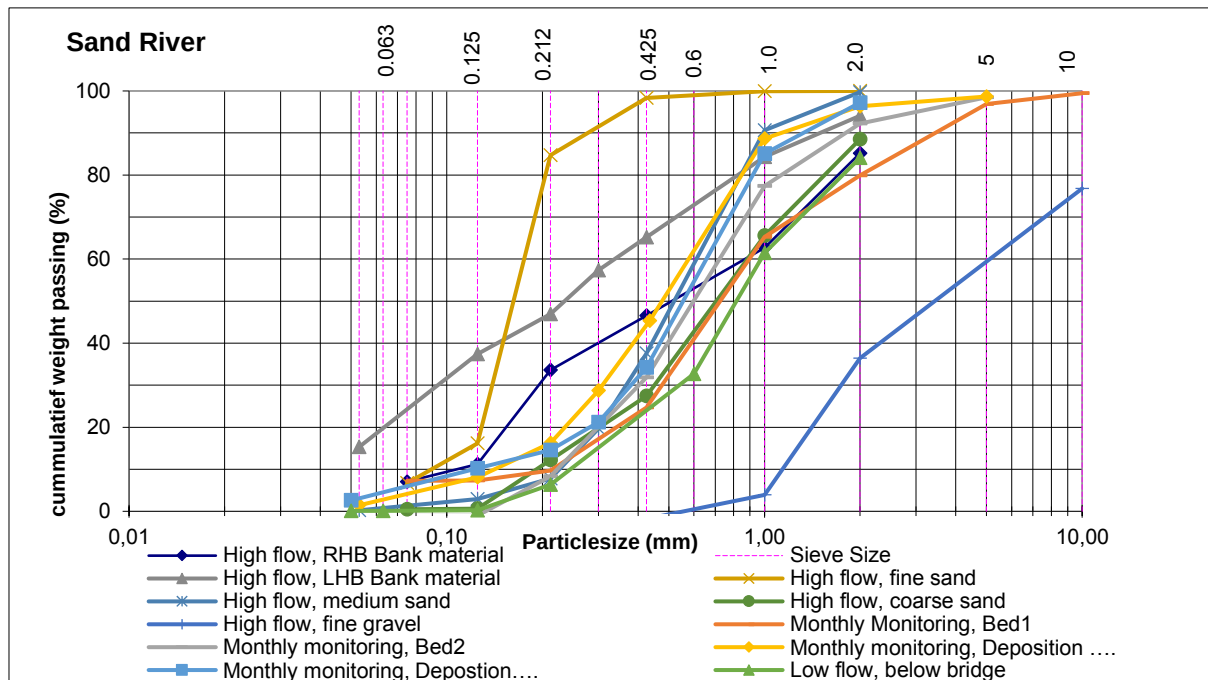




Sediment analysis

The sediment samples taken at Sand river were for high flows taken per grain size; fine sand, medium sand ect. For EFA low flow survey the sediments were taken with a grab sampler under the bridge, this is a representative sample for all the sediment that is transported from upstream the catchment.





Suspended sediment

The values for suspended sediment with relation to discharge are given here. These are data from the field and from literature

Q (m ³ /s)	Turbidity (NTU)	SS (mg/L)	Source
0.6	837,807	1000,1050,890	Field measurement
<? (8-01-2015)	34.1	30	Field measurement
<?		19.2	Field measurement