Rapid hydraulic assessment tool for river floods using hydraulic geometry relations in data scarce areas.

Ain't no river wide enough

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Preface

First I would like to thank a few people who made this research possible. At first professor Nick van de Giesen and Transformative Environmental Monitoring to Boost Observations (TEMBO). Without them I never would have had this opportunity. Second I would like to thank Josiah Kahuthu from the Kenyan Metereological Department and Anne Wamuyu of the Narok county government Department of Environmental Energy, Water and Natural Resources. They guided me and helped with my research in Kenya. At last I would like to thank Tim Leijnse and Roel de Goede from Deltares. They helped me a tremendous amount with the set up for SFINCS simulations. A

TEMBO Africa*: The work leading to these results has received funding from the European Horizon Europe Programme (2021-2027) under grant agreement n° 101086209. The opinions expressed in the document are of the authors only and no way reflect the European Commission's opinions. The European Union is not liable for any use that may be made of the information.*

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Introduction

It is difficult to accurately measure river discharge. Even with modern technology and efforts of various engineers, it could not be simplified to one simple measurement and calculation. With time, more tools and technologies have become available to determine river discharge. For the most realistic calculations, a lot of measurements and a lot of time is needed, both of which are not always available.

1.1 The importance of data

With the development of humanity, data has become more and more important. Over the past 100 years, decisions are increasingly based on data and measurements. Trends are being discovered in a well monitored modern world. One of these trends is climate change. With global warming, the weather has shown more extreme conditions over the years. Periods of long drought, followed by short high intense rainfall are more common. These developments influence the river discharge as well. More rain falls in a shorter period of time with the ground unable to absorb all of the water. The water flows to the river, raising the water level rapidly in the river. The maximum capacity of rivers, or the bank full state, indicates the peak amount of water flowing through a river. With the bank full state being reached more often, the possibility of floods is also rising. Typically, a river's bank full state indicates a flood of the flood plain that occurs about every two years (Williams, 1978a). The data to monitor a river's bank full state and discharge during a flood is necessary for local population development near river banks. However in rural areas, such as in Kenya, Africa, cities are developing around rivers without the means to monitor this necessary data and plan accordingly. Floodplains are being occupied by the population without the proper measurements or knowledge of the local river discharge. Methods have to be developed to help settle local population in these floodplains without the time to collect the data.

1.2 The city of Narok

In modern time, the use of land has shifted tremendously, also in Kenya. The population moved together to villages and cities, increasing population density. Over the past decades, almost 30% of the population moved into urban areas in Kenya. They also moved into small cities like Narok. Narok is a small city placed near the river banks of the Enkare-Narok river. Narok is a fast growing city of approximately 40.000 people. These people settle on either side of the river. To cross the river, a bridge was built in the town. The bridge was built to cross the river during the dry season. No data was available of the river discharge in a bank full state. This led to multiple floods in the city of Narok. It is more common now with climate and land use change. The infrastructure built to help the local population cross or guide waterbodies, often increases the occurrence of flash floods (Srinivasa Rao et al., 2019).

A closer look into Narok city, shows that all factors mentioned above apply to this town. Narok has built the city on the river beds of the Narok-Enkare river. They have also built a bridge to cross the river. Narok has encountered flash floods in the past for several reasons. Due to climate change more intense precipitation has fallen during the rain period. The bridge's maximum capacity of river discharge is lower than the rivers maximum capacity in a bank full state. And this happened partially because no reliable data regarding the Enkare-Narok river discharge is available.

To reduce the negative impacts of extreme weather, various projects have risen to help countries in Africa to gather this data. One of these projects is TEMBO: Transformative Environmental

Monitoring to Boost Observations in Africa, funded by the European Horizon Europe Programme. TEMBO aims to bridge the environmental data gap in Africa. Through its endeavours, TEMBO strives to develop systems that contribute to the well-being of populations by utilizing available environmental data. These systems encompass Flood Early Warning Systems (FEWS), reservoir management, and agricultural information.

In the specific context of Narok, the intensification of precipitation, results in more frequent flash floods. Despite mitigation efforts by the city of Narok during the prolonged rainy seasons, annual river floods persist. Initiatives like TEMBO and the Trans-African Hydro-Meteorological Observatory (TAHMO) have initiated steps, including the establishment of weather stations for FEWS. However, the critical aspect of measuring river discharge during flood events remained inadequately addressed.

1.3 Research objective

The primary objective of this research is to facilitate the development of Flood Early Warning Systems (FEWS) in Narok and similar towns through the comprehensive measurement of hydraulic data pertaining to flood events. The objective is to predict the extent of the flooded area in Narok during typical flood events without long time series of discharge or level observations.

Several assumptions were made during the research process. The first assumption concerns the root cause of flooding in Narok, namely the bridge constructed over the river that severely reduces the cross-sectional area, resulting in a reduced discharge capacity compared to the river's natural maximum. Consequently, water levels rise upstream, surpassing the riverbanks.

Second, we assume that the hydraulic geometry can tell us a lot about the capacity of a river to accommodate discharge. By measuring a canal's width and depth in conjunction with water velocity, discharge can be estimated. In turn, this discharge measurement can serve to estimate important hydraulic parameters such as the hydraulic roughness. This method aids in estimating river discharge, representing an essential facet of hydraulic analysis (Leopold & Maddock, 1953). However, real-world scenarios introduce a myriad of additional factors that significantly influence the calculation of river discharge. Initial calculations consider the measurement of depth, width, and hillslope to estimate the maximum discharge of natural rivers (Yan et al., 2014). For this reason, additional checks were made on the robustness of the estimates using the Leopold and Maddock method.

A third assumption pertains to the definition of the natural maximum capacity, drawing on insights from (Williams, 1978b). The focus lies on the bank full definition, which involves examining the active floodplain. In this context, visible flood marks and evidence of erosion on the floodplain's edge contribute to determining the bank full capacity (Bösmeier et al., 2022). Also discussion with citizens helped to determine maximum water levels.

The definition of a flash flood is given in (Hoedjes et al., 2014). A flash flood is described as a flood that rises and falls quite rapidly with little to no prior warning. For the purpose of this research the flash flood will be simulated over half an hour without prior water level rise, based on discussions with local citizens.

Finally, the assumed discharge of the bank-full state will be calculated by Manning's equation. Leopold's method and parameters for width, depth and velocity are applied to ensure a verification of the calculated discharges. The combination of both equations increase the trust in the overall method and parameters.

The combination of these measurements and assumptions forms the basis for constructing a Super-Fast INundation of CoastS (SFINCS) model (Leijnse, 2023). This model serves as a comprehensive tool to evaluate the validity of hydraulic geometry as a method for determining realistic discharge values in data-scarce regions during flood events. SFINCS serves to model the flooding in Narok during flash floods in terms of speed, flow, and duration.

This summarizes the research objective: *To design a hydraulic model based on hydraulic geometry and determine the area of floods in a SFINCS model in Narok as typical case of a data scarce area*.

Chapter 2: Method & Material

2.1 Study area

The study was conducted within the floodplain of the Enkare-Narok river in Narok town, Kenya, as depicted in Figure 2.1. Three water bodies converge in Narok town, two drainage canals and the Enkare-Narok river. The river's outflow is situated to the south of the town, downstream of two main bridges. The research emphasizes the impact of these bridges' bottleneck effect and the natural maximum capacity of the river. Specifically, the investigation seeks to how much of the town's area is flooded when the natural maximum capacity of the river is reached.

The hydrological relationships within the upstream areas of the canals and rivers are excluded from the scope of this research. The research narrows its focus to three primary aspects: the determination of the maximum discharge of the river based on the bank-full concept, the bottleneck effect created by the bridges, and area flooded as the result of the overflow of water beyond the riverbanks into the town. This research aims to understand the intricate dynamics of these key elements to contribute valuable insights into flood mitigation strategies in Narok and similar regions grappling with similar challenges in terms of data scarcity.

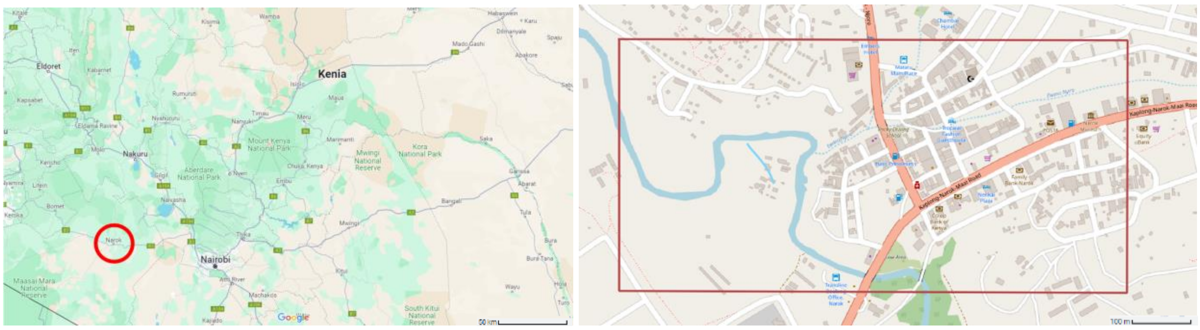


Figure 1: Map of Kenya on the left with Narok marked west of Nairobi an map of Narok town with in red the outline of the area used in the flood model (maps.google.com)

2.2 Method overview

Below is a summary of the developed method during this research. Through field measurements, cross sections and a velocity profile could be estimate at several places along the river. The field measurements consisted of topographic observations collected with cost-efficient GPS equipment and of the measurement of water flow velocities at the surface of the river. In turn, these are used to calculate Manning's coefficient for Manning's formula for discharge through a river or canal. Manning's formula is then used to calculate a discharge for the fitting cross section in a bank full state of the river. This ends the first part of the tool, which resulted in viable cross sections and corresponding discharges in a bank full state. Bank-full refers to the water level in the river where the water stays just between the natural levees of the river and does not yet flood the adjacent floodplain. Because we make use of the bank-full morphology of the river, we do not need a long time series to determine the area at risk during floods. In general, one can expect that the natural channel of a river accommodates a flood that occurs between twice per year and once per two years (Williams, 1978).
To further examine the consistency of the results, we look into Leopold's method, which proposes logical relations between the discharge and the width, depth, and water velocity of a

river cross-section. To estimate the parameters of Leopold's method, discharges and cross sections were graphed against each other to find the assumed exponential hydraulic relations. This results in the Leopold's parameters. It is important that Leopold's parameters are mathematically consistent, which gives an indirect form of verification for the measured data. For this tool, the discharge is calculated again with the formulas of Leopold, Leopold's parameters, and the measured data. This gives Leopold's discharges in the tool for bank-full which are used for the hydraulic model.

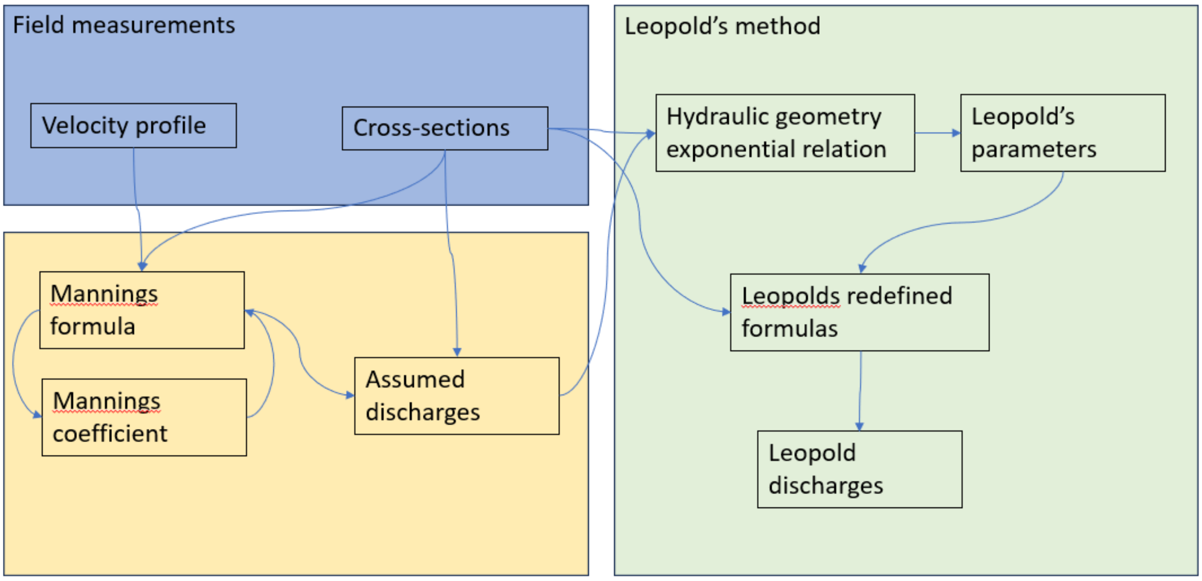


Figure 2: Methods overview in 3 parts. Field measurements, Manning calculations and Leopold method.

2.3 Discharge estimation

A lack of data is a concern for hydraulic research in most of Africa. Long droughts followed by intense precipitation lead to flash floods. This is also the case in Narok, Kenya. The best way to determine the discharge of a river is with direct measurement. However there is no equipment available for these measurements.

2.3.1 Manning equation for discharge

$$Q = A * \left(\frac{1}{n}\right) * R^{\frac{2}{3}} * S^{\frac{1}{2}} \qquad [1]$$

Calculation of the river discharge is an alternative possibility. With the help of the Manning equation, a river discharge can be estimated. There are multiple parameters needed for the calculation of a river's discharge. For the calculation of the discharge Q (m^3/s) is a cross-section A (m^2), slope S (-), Hydraulic radius R (m) and Manning coefficient n ($s/(m^{1/3})$) needed of the river bed. The cross-section of the river can be calculated with precise coordinate and elevation data. This gives the total surface of the riverbed. A cross section also provides the hydraulic radius. The hydraulic radius is the ratio of the cross section to the wetted perimeter P (m). The wetted perimeter is the surface of the river bottom and sides in direct contact with water.

With multiple cross-sections, the slope of the riverbed can also be calculated. This is possible by determining the elevation data of the riverbed from multiple measurement sites. The

difference in elevation is divided by the length of the river between the sites. This is necessary to determine the velocity of the river discharge.
With a survey of cross-sections, a reasonable assumption can be made for the discharge of a river due to the Manning formula. Only parameter missing is Mannings coefficient. This coefficient is not measured in a traditional way and will be discussed later in the research. These cross-section can be made with the help of satellites in the Global Navigation Satellite System (GNSS)

2.3.2 GNSS Survey

2.3.2.1 GNSS Ardusimple measuring kit

The GNSS is a general term describing any satellite which helps with positioning or timing on a global scale *[gps.gov]*. Satellites can give precise coordinates on a position on Earth. GNSS works with receivers on Earth to determine the position of the receivers. For a singular receiver, GNSS has an error factor of 2 meters. This is due to the atmospheric disturbance *[Ardusimple.com]*. To prevent this error, it is possible to put 2 receivers within 100 metres of each other. This will give the same atmospheric disturbances for the same points. Thanks to the 2 receivers, the distance between the 2 points can be calculated with 1 centimetre accuracy. This is the basis for Real-Time Kinematic (RTK) technology. One of the receivers is in a fixed known position, which is called a Base station. The Base sends corrections to a second moving station, called a Rover. The Rover uses these corrections to determine centimetre precise positions.

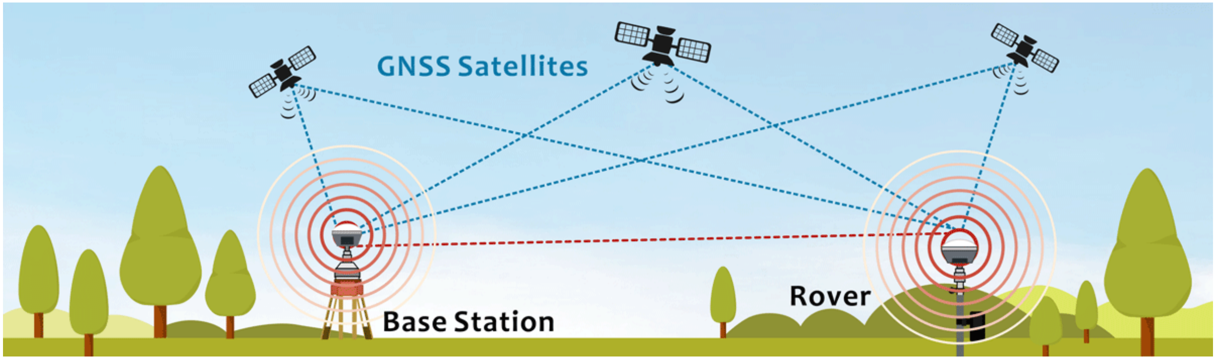


Figure 3:GNSS example (https://www.unictron.com/wireless-communications/tpost/rtk-gnss/)

The coordinates and elevation data of the positions are used to calculate the hydraulic-geometry relations of the river. This data is acquired using an RTK2B Ardusimple Starter Kit LR, comprising two Multi-band Active GNSS Antennas and two Evaluation Boards (Base and Rover) [*Ardusimpel.com]*. The deployment of this kit facilitated an enhanced accuracy range, reducing from 2 meters to 1 cm under optimal conditions. This kit has made it possible to complete this type of research. Due to technological advances this kit is available for worldwide use. With this kit comes a worldwide available program as well, u-blox. Employing the u-blox program which helps register the coordinates from the Base and Rover. U-blox sends the corrections from the Base to the Rover so the Rover has a more accurate position [*Ardusimple.com*].

2.3.2.2 Set-up of measurements

The Ardusimple Base was placed on a tripod to make sure it did not move. For a duration of one hour the Base is collecting data to ensure a fixed position. After enough data is collected, it can ensure an accuracy of 1 cm. The rover was fixed to the top of a 2-meter measurement pole. At each point where the elevation needed to be measure, the pole was placed vertically. The pole served as a walking aid during river traversal, ensuring the equipment remained dry. The pole also aided stabilization during high water velocities, facilitating a straight walk from bank to bank. A distance of approximately half a meter was maintained as measurement intervals. This interval was chosen for several reasons. The river width in Narok was estimated tin between 25 and 50 metres. This gives in between 50 and 100 steps each crossing. The accuracy of 1 centimetre is also acceptable with steps of 50 centimetres. At last the average step is 50 centimetres, especially when measurements are taken in the middle of the river.

2.3.2.3 Measurement sites

The measurements are taken at various locations near Narok in the river. After interviews with the local population, 4 sites were chosen for the measurements. In the figure below the four sites are marked with an X. Also the floodplain is marked, which is between the river and the two main roads of Narok. To explain the measurement sites from left to right. The first measurement site “Upstream” is upstream of the town of Narok, where there are no man-made modifications to the river. There is also no back water curve of any man made modifications to the river. The river banks are very naturally formed. The second site is called “Canal”. This is where the rain water from the northwest of the city is collected and enters the river. This is also the flood point location. The river bed is the lowest here and the river floods from this location. The third site is the “Bridge”. This is the man made bottleneck. The assumption is the backwater curve from this bottleneck causes the flood from the river. Therefore a cross-section from this site is necessary. At last the last site is called “Downstream”. This is a similar place as “Upstream”. So this has a natural river bed with any man-made modifications to transport the natural river discharge.
At the sites multiple measurements are taken to ensure the accuracy of the cross-sections. The accuracy of the measurements could be off due to buildings and trees on the river bank. With multiple measurements there was also a learning curve in the use of the Ardusimple kit. The last measurements had no inaccuracies. This lead to every site having at least two similar accurate cross-sections. Every site was therefore crossed two to four times. And every crossing is used for a measurement.

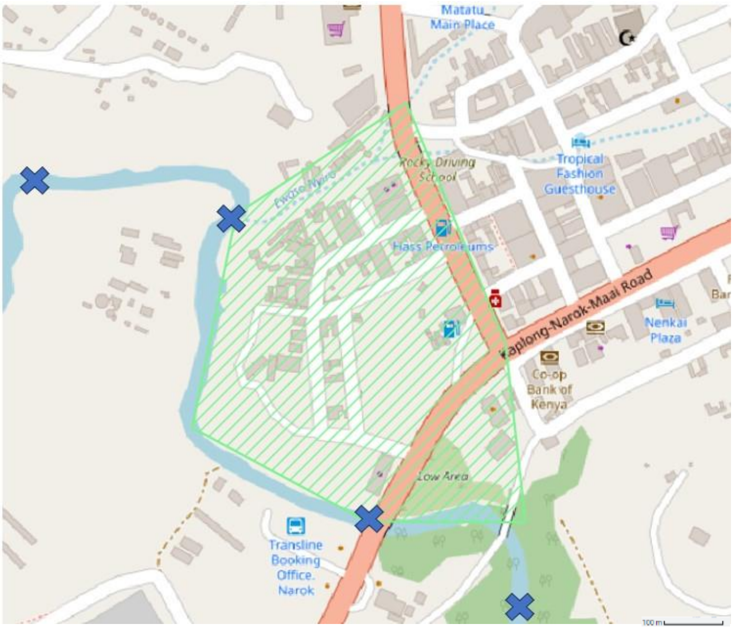


Figure 4: Measurement sites and flood plain (QGIS)

2.3.2.4 Inaccuracies in measurements

For the registration of the points during the crossing is also an app and an Android phone necessary. This application is called SW Maps. SW Maps allows you to pin and save the location of the Rover. The location service of the phone needed to be turned off. The exact description on how to register the coordinates and elevation of the rover in the application SW Maps is given in Appendix A. The app indicates when the Rover achieved optimal position accuracy after a few seconds. Coordinates and elevation data were recorded in the app from bank to bank to obtain a profile. Multiple attempts were conducted on different days and locations due to potential interference from vegetation and buildings alongside the river, impacting the signal of the Base and Rover, which could affect accuracy *[Ardusimple.com]*. A river cross-section with measured points, as illustrated in the SW Maps application, is depicted in the figure below.

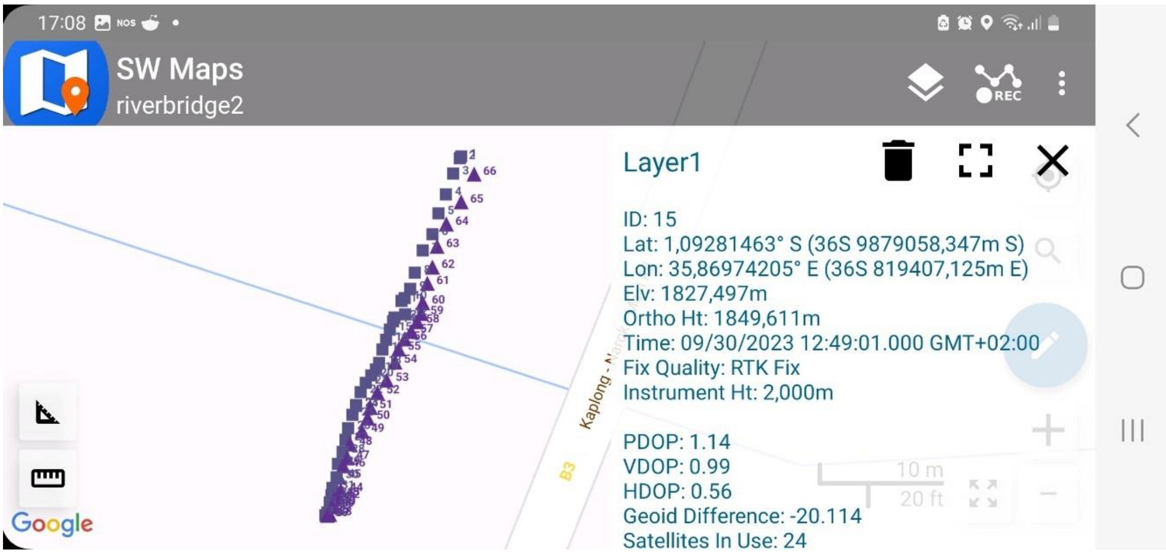


Figure 5: SW Maps example of bridge crossing day 2

2.3.2.5 Data conversion to Python

Upon completion, multiple lists in the SW Maps app contained coordinates and elevation data for various river sites. These lists were exported through Excel and prepared for Python scripts. These scripts, provided in Appendix A, facilitated the identification of inaccuracies in the elevation data of the steps. Some inaccuracies in the coordinates were already evident in the SW Maps app. As seen in the figure above the points form a straight line. If a point was not measured accurately the point would not fall on or near the line which was followed during the crossing of the river. Inaccurate coordinates and elevation data were discarded if they significantly disrupted the cross-section calculations, and the surrounding points were deemed accurate enough to establish a connection without the discarded point. With steps of 50 centimetre, the inaccuracies were deemed inaccurate if they were over 25 centimetre in elevation data. The riverbed was crossed several times and sudden elevations were avoided.

2.3.3 Velocity profile

One of the variables crucial for the simulation, which had to be derived from other variables and could not be directly measured, is the Manning coefficient. The Manning coefficient signifies the roughness of the riverbed, influencing the water velocity. This is significant, given that velocity is one of the three variables affecting river discharge, and the relationship between velocity and discharge is investigated through Leopold's method, as will be discussed in 2.4.

2.3.3.1 Velocity tests

To estimate the Manning coefficient, the velocity of river discharge was measured during a low discharge state. Oranges were released into the river, and their time of travel over a pre-measured distance of 10 meters was recorded to determine the top velocity of the river discharge. All the results of the tests are given in Chapter 3.

2.3.3.2 Bed elevation and slope

Another vital variable in the calculation of river discharge is the bed slope of the river. This was obtained by measuring cross-sections of the river at different sites. Several points in the middle of the river were chosen and averaged for bed elevation. This was done for the four chosen measurements sites to determine the slope. The slope was calculated between the two outermost sites and between the two inner sites The distance between the two outmost site is approximately 1850 meters. The distance between the Canal and the Bridge is 350 meters.

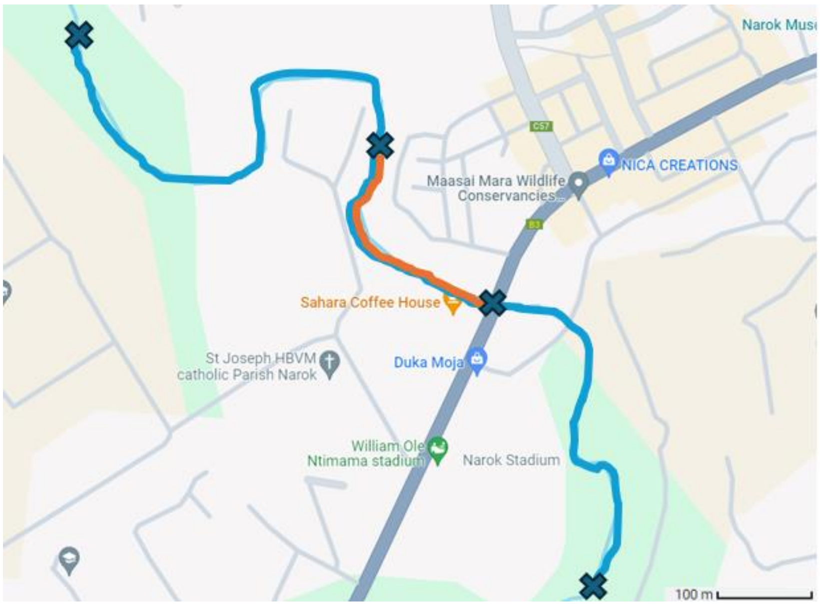


Figure 6: Narok river with markings of inner and outermost slope (maps.google.com)

2.3.3.3 Velocity profile and roughness coefficient

The exponential velocity profile was employed to calculate the average velocity over the total depth of the river during low discharge. This calculation is illustrated by the equation below. It is based on a fully developed turbulent flow profile (Von Karman, 1930). With z as height above bottom of the stream (m), v as time-averaged velocity (m/s), $C=u^*/\kappa$ (m/s) with u^* as friction velocity (m/s) and κ (-) the von Kármán constant, usually taken as 0.4 (-), and z_0 the depth at which the velocity equals zero. As the measured surface velocity was measured in the middle of the stream, where the water depth was about one meter, the effect of the side walls on the flow profile will be neglected and we concentrate on the effect of the bottom on the flow profile.

There are two unknows in the formula below *C* and z_0. The only know variable is the velocity at the river surface $v(z_{max})$. In order to fit the profile that matches the surface velocity, an iterative process was done to calculate *C*. For a normal smooth, sandy bottom, as observed in Narok, z_0=5mm is often found in the literature (Smart et al., 2004) . A sensitivity test was done with *C* to find the corresponding friction velocity u^*. The friction velocity for rivers corresponds between 0.05 and 0.1 of the average velocity, which could be applied to the formula (Zimmermann & Church, 2001). In the sensitivity test u^* was tested from 0.05 to 0.1 to fins the corresponding maximum velocity. All values of *v* were then calculated over the total depth per millimeter, and divided by z_{max} to obtain v_{avg}.

$$v(z) = C \cdot \ln \frac{z}{z_0} \qquad [2]$$

Calculations were done with the cross-section of a site during low discharge. The site which was used is "Upstream". This site was chosen because this part of the river was closest to a natural river discharge without man-made infrastructure. The calculated average velocity was used to calculate the Manning coefficient *n* (s/[m1/3]). The Manning equation is given below again. With all the data from the low discharge state and the measurement site 'Upstream', the Manning coefficient was calculated. This coefficient was then applied to the entire river to calculate the river discharge during a bank-full state.

$$v_{avg} = \frac{Q}{A} = \frac{1}{n} \cdot \sqrt{S} \cdot R^{2/3} \qquad [3]$$

2.4 Leopold & Maddock method

The Leopold & Maddock method assumes an exponential relationship between the hydraulic geometry of rivers and their discharge (Leopold & Maddock, 1953). In the research of Leopold the geometry includes the width of the water at water level (w) in meters, as well as the mean depth of the water (d) in meters. Finally, there is average velocity (v) of the river discharge in meters per second. Leopold and Maddock also researched the relationship between the sediment and the discharge of the river. However this is not relative for this research.
Leopold & Maddock assumed a set of exponential relationships. The method defined the relationship through three formulas and six extra parameters. These formulas and parameters are given below.

$$w = a * Q\hat{}b \qquad [4]$$
$$d = c * Q\hat{}f \qquad [5]$$
$$v = k * Q\hat{}m \qquad [6]$$

$$w * d * v = Q \qquad [7]$$
$$b + f + m = 1 \qquad [8]$$
$$a * c * k = 1 \qquad [9]$$

Each formulas has 2 parameters, a multiplier (a, c, k) and a power (b, f, m). These parameters give an exponential relationship between the discharge and the hydraulic geometry. In Leopold's research this relationship is portrayed by a graph on a logarithmic scale. A requirement for the relationship between hydraulic geometry and the discharge is given below the formulas. The multipliers have to multiply with each other to one. The powers have to add to one. This makes the relationship between the parameters and the discharge mathematically (and physically) correct. This is also the main goal of this research. To solve for Leopolds parameters and find the relationship between the discharge and hydraulic geometry without available long term data.

2.4.1 Leopold in data scarce areas

Leopold's method has evolved over the years to estimate the river discharge in data scare areas. Its method has grown more into finding good relationships between the hydraulic geometry and the river discharge for rivers in different climates. However a perfect relationship is difficult and nearly impossible as multiple researchers has shown over the years. One example is the research of Gleason & Smith. In 2014, Gleason & Smith tried to develop a method based on Leopold by using satellite imagery to determine the discharge of large rivers. This research was only based on the width of the river and used on rivers with a width bigger than 100 meters. Where discharges were known for the rivers, their estimations based on satellite images had a maximum error of 30% of measured discharge. In follow-up research, Gleason & Smith extended their scope by including a larger spectrum of river sizes and climates. With different climates and environments, they concluded that the satellite-based method had an error rate of up to 40% error in discharge. However this method cannot be applied for rivers smaller than 100 meters. The error rate would be too high due to the coarseness of the satellite images. Leopold's method is presently mainly used to determine the river discharge in areas where there is no data available, especially for wide rivers.

Leopold's method has also been applied for small rivers as well. In 2021 Grison did research to test Leopold's method for smaller rivers with detailed measurements. It was tested for a small basin in Brasil (Grison et al., 2021). The conclusion was that Leopold's method could be effective for small rivers to estimate the discharge with enough data.

2.4.2 Bank-full state with hydraulic geometry

Presently, Leopold's method is seen as a reasonably accurate way of predicting the discharge of a river if field measurements are not available. In Leopold's original research, the average depth was used, also because Leopold's original research focused on average annual discharge. In this research the focus lies on flash floods and maximum discharge. Therefore hydraulic radius will be used as a parameter in the hydraulic geometry (Lawrence, 2007). Hydraulic radius is more suitable for open rivers than average depth. The hydraulic radius is defined as the wetted cross-section (A) divided by the wetted perimeter (P). Note that for wide shallow rivers, average depth and hydraulic radius converge.

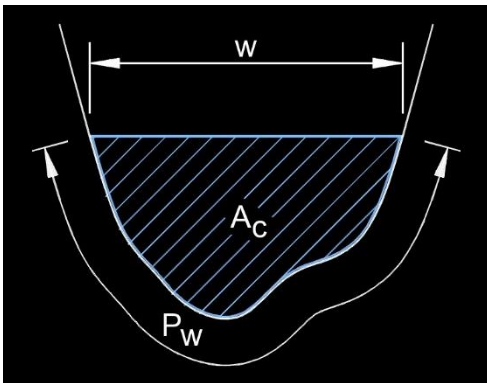


Figure 7: Representatiom of hydraulic proportions to calculate hydraulic radius. (https://www.piping-designer.com/index.php/properties/fluid-mechanics/2248-hydraulic-depth)

Another important concept regarding the river discharge is the bank-full state of the river. Here, bank-full is defined as the water level at which the natural levees are just not overtopped. Once the natural levees are overtopped, we speak of actual flooding. In 1978 Williams noted that once the levees are overtopped and the floodplains fill up, Leopold's hydraulic geometry is no longer useful for calculating the discharge effectively. We use bank-full here to determine the regular maximum discharge levels that are reached, on average, once per one or two years. When the river then meets a man made bottleneck, such as the bridge in Narok, flooding will typically start there.
To determine the bank full state, flood marks have to be inspected. Over time floods can give various marks in the landscape (Bosmeier, 2022). Nature on the riverbanks give a clear indication on how high the water can rise. If it occurs on a yearly basis the marks are very clear. For confirmation also the help is asked of the local population to determine the water height.

2.4.3 Redefining Leopold

After these clarifications, the actual use of Leopold's method in this research will be explained. To summarize, Leopold's method is used in present-day research to develop a quick method to determine river discharge in data scarce areas. This is also the goal of this research. However, we use Leopold in a slightly different matter because we do have observations of the water velocity at the surface, which allowed us to determine the Manning coefficient. Together with measurements of the river bed (cross-sections and slopes), we can calculate the river discharge in a bank full state using Manning's equation. This calculated discharge was then used to determine the multiplier and exponential parameters for the width, hydraulic radius and velocity for the various measurements sites. These parameters are then used to calculate new discharges based on the width, hydraulic radius and velocity. This is done by re-writing Leopold's formulas as shown below. If all measurements and approximations are correct, Leopold's parameters have fit the constraints. The bank-full discharge according to Leopold's re-written formulas were used for simulation of the floods.

$$Q = (w/a)^\wedge(1/b) \quad [10]$$
$$Q = (d/c)^\wedge(1/f) \quad [11]$$
$$Q = (v/k)^\wedge(1/m) \quad [12]$$

2.5 Hydraulic numerical simulations

2.5.1 QGIS DEM preparation

Before we can start numerical hydraulic simulations, pre-processing of the input data is needed, especially regarding the topography. QGIS was used for the preparation of the Digital Elevation Model (DEM). QGIS is an open source, online available Geographic Information System (GIS). QGIS has been used for various hydraulic models at different scales. Open source and previous use are the main reasons for the choice of QGIS in the preparation of the DEM.

To generate one's own DEM of one particular area would take a lot of time for field surveying. In this research neither the time or the equipment was available to make a detailed DEM. Instead, we use data from the Shuttle Radar Topography Mission (SRTM) DEM, with cells of 30 meters by 30 meters for almost every country. These cells are a bit coarse, especially because the river is not wider than 30 meters at some points. In QGIS it is possible to change the size of the cells to 1 meter to 1 meter. This is shown in the figure below.

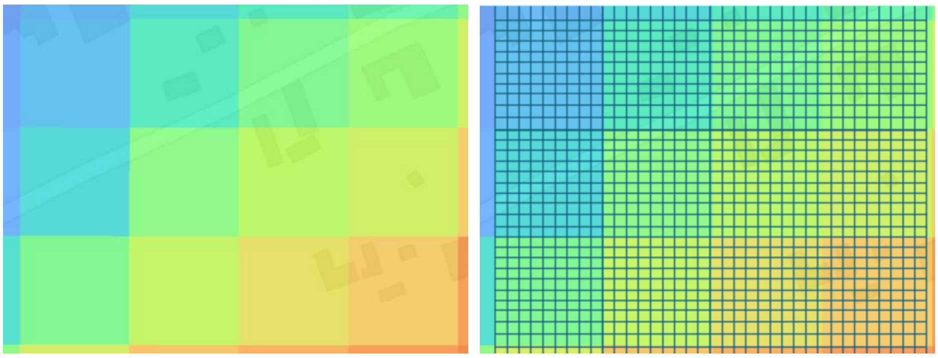


Figure 7: On the left a part of the DEM of Narok unaltered. The colours represent different levels of elevation. On the right a small raster is pictured on top of the DEM with smaller cells but still with the same elevation data.

The importance of the cell size will become clear when the hydraulic geometry of the river is discussed. As mentioned before, the river has a smaller width than 30 meters in Narok. Therefore it is not possible to adjust cells in QGIS to model a river when the cells are bigger than the river itself. With cells of 1 meter by 1 meter, the river could easily be modelled by adjusting the cells which coincide with the location of the river.

The hydraulic geometry of the river has been measured at several places (see 2.3.3). For different parts of the river there are different widths and average depths of the river. Through a process called 'burning', the elevation data in cells can be adjusted so river can flow through the DEM without being "dammed". Because the cells size are adjusted to 1 meter to 1 meter, the rivers width could be adjusted with a precision of 1 meter. The adjusted DEM of Narok city with the burned river is shown below. The difference in elevation between the river and surroundings is shown with the different colours.

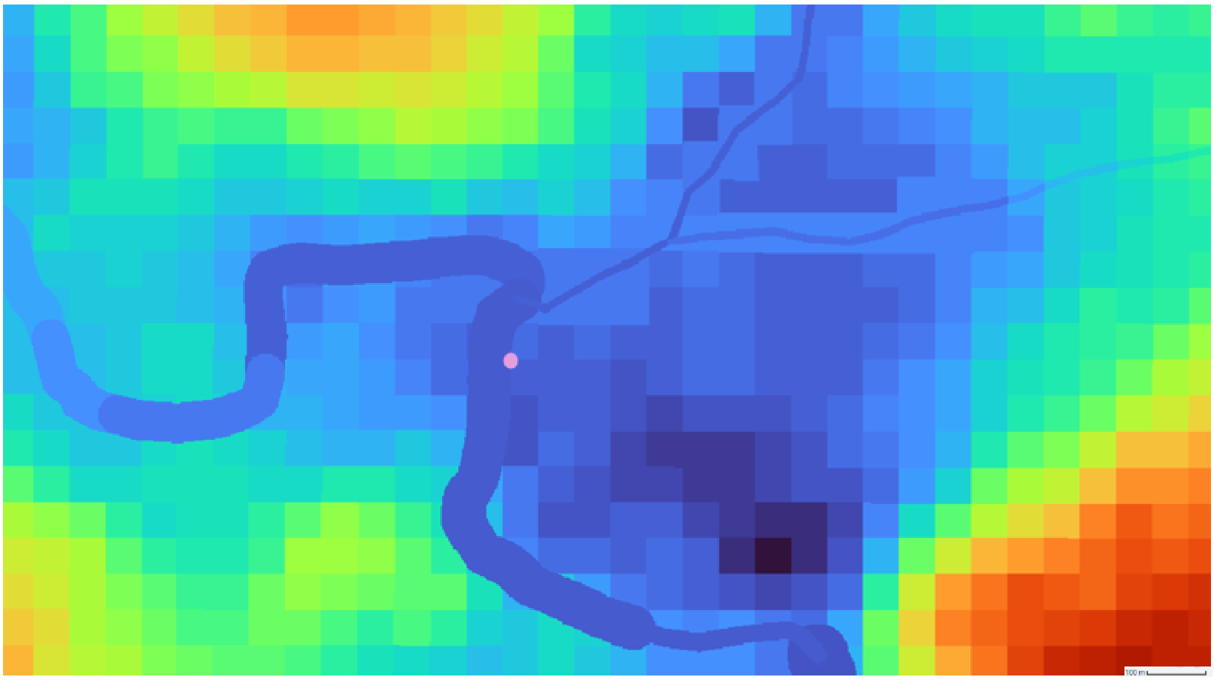


Figure 8: Adjusted DEM with burned in river and marked flood point (QGIS).

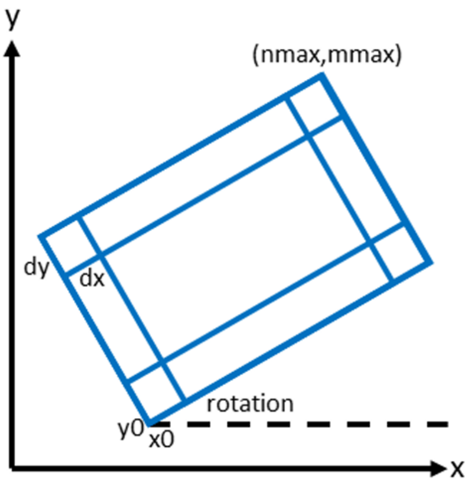
The burning process is important for the correct functioning of a hydraulic model as it prevents the model from flooding areas that in reality do not flood. Places where water overflows from the river into the adjacent floodplain are called “flood points”. Due to the roughness of the DEM, several flood points can occur if the burning is not done carefully. Before the adjustment of the DEM, the local population was interviewed to discuss the previous floods which occurred in Narok. A singular flood point was determined in the DEM by examination of the river banks and discussions with the local population. It is just downstream of measurement site Canal and also marked in the figure above.

The importance of the flood point is also reflected in the slope of the riverbed. Due to the roughness of the DEM, the elevation of the river bed has to be burned in manually. This means the river bed in the DEM jumps from one elevation to another elevation to reconstruct the slope over the total length of the river. Instead of a smooth slope in the riverbed. These jumps in riverbed elevation are chosen carefully in the length of the burned river, so there are no unrealistic flood points. With a pre-processed DEM in place, we can now turn to the actual hydraulic simulations.

2.5.2 SFINCS preparation

The Super-Fast INundation of CoastS (SFINCS) model was developed by Deltares. Even with a pre-processed DEM some preparatory steps with Hydro-mt are needed before SFINCS can be used. With the help of Hydro-mt, a Python based program from Deltares, data can be prepared for simulations in SFINCS. This is all available for Windows and can run on a standard laptop, which makes it very available.

The first part of the data preparation is the coordinate system. The coordinate system is important because it has to overlap with the DEM. Together, coordinate system and DEM define the elevation data for the SFINCS model. An example is shown in the figure below. Coordinates are needed from the left bottom corner of the DEM (x0, y0). Similar to the preparation of the DEM in QGIS, Hydro-mt also uses a grid with cells. The number of cells (nmax, mmax) and the size of the cells (dx,dy) need to be registered in Hydro-mt in meters. The size of the grid in Hydro-mt cannot be bigger than the size of the DEM. If desired the grid can also be rotated in degrees from the x-axis in anti-clockwise direction.




```
x0              = 0
y0              = 0
mmax            = 100
nmax            = 100
dx              = 100
dy              = 100
rotation        = 0
```

Figure 9: Example of coordinate system in SFINCS (SFINCS manual)

When the location and elevation data is prepared for the SFINCS model, other parameters are also necessary for the configuration of a SFINCS model. SFINCS can be a very detailed model with a lot of parameters. Due to the fact that it is used in a data scarce area, the minimal parameters for a SFINCS model are discussed here. Below is screenshot of the configuration in Hydro-mt.

On top of the configuration are the time stamps. This dictates how long the SFINCS model runs. If hydrological data are available the precise date and time are of special importance.

```
sf.setup_config(
    **{ "tref": "20230101 000000",
        "tstart": "20230101 000000",
        "tstop": "20230101 040000",

      "res": 10,                # model resolution (10)
      "crs": "utm",             # model CRS (must be UTM zone)

      "manning": 0.0516 ,       # Manning coefficient
      "manning_land": 0.0516,

      "dtout": 300,             # This is for every 300 secoond SFINCS makes a measurement
      "theta": 1,               # Should always be 1
      "alpha": 0.1,             # alpha can be between 0.1 and 1
      "qinf": 2                 # Infiltration rate of the ground
    }
    )
```

Figure 10: SFINCS configuration in Hydro-mt

The “res” and “crs” variables are resolution and coordinate reference system, respectively. The resolution is the number of meters per pixel and can vary up to 500. For the crs it is important to use the Universal Transverse Mercator (UTM). It is a global map projection which helps SFINCS to locate the model and use any data which is linked to the model location.
The Manning coefficient (manning), can be used for a general Manning coefficient, but also split in a sea and land Manning coefficient in SFINCS. In this research both general and land Manning coefficient were specified.
At the end there is the infiltration rate (qinf) for the model. It is in millimetre per hour. If this is not set in the configuration the default value in the SFINCS model is 0.
The other three, “dtout”, “alpha” and “theta” are related to the model runtime of SFINCS. “dtout” is the number of seconds between each output in SFINCS. The smaller the number, the more outputs within a given period of time but also the longer the runtime. The parameter “alpha” is an additional timestep limiter that can never be higher than 1. If the model in SFINCS does not run smooth it is advised to lower “alpha” until 0.1. The parameter “theta” sets the implicitness of the numerical scheme of SFINCS and should always be set to 1 in the configuration because fully calculations tend to be more stable than (partially) explicit calculations.

With the model set up and configured, the water can be added to the hydraulic model. One important property of the SFINCS model is the ability to run empty. The SFINCS model needs special borders where water can flow in and out of the model. Without an outflow point, the model will fill up with water and SFINCS crashes. A way to do this is to set a water level around the border of the SFINCS model. The water level boundary (waterlevel bnd) sets a water level at the boundary at the model at a certain elevation. The boundary is set everywhere around the model where the elevation is lower than the set water level. Water in contact with the boundary reaches a balance with the water level and flows away out of the model. This boundary is shown in the SFINCS model down below.

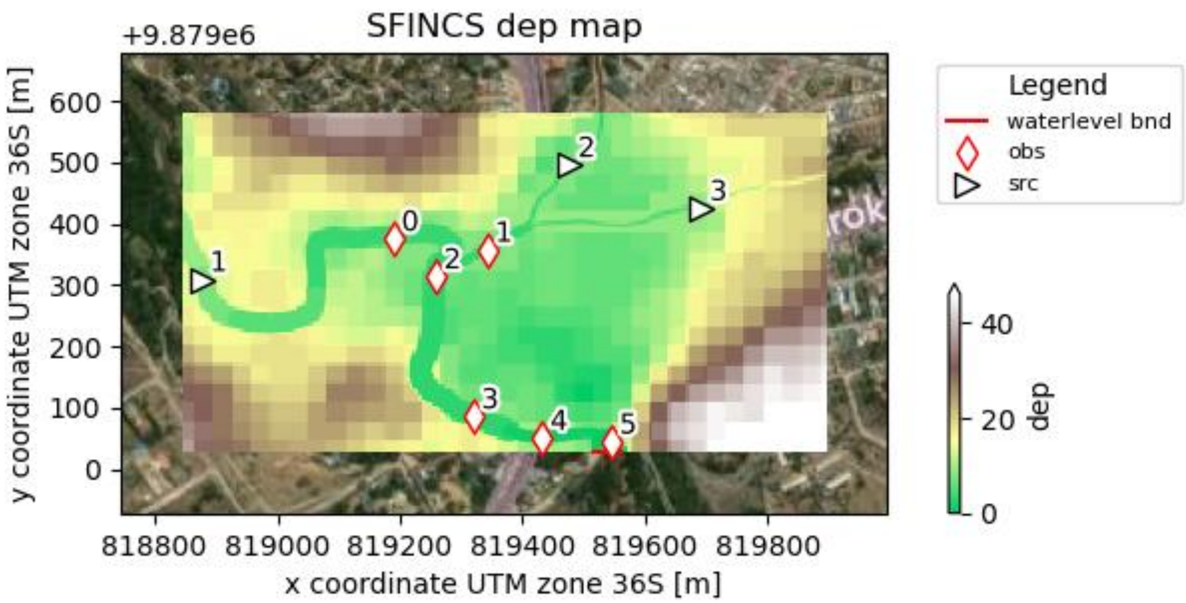


Figure 11: SFINCS map of Narok city with water level boundary, source and observatory points

To add water in a SFINCS model, there are various ways. For data scarce areas it is easy to set up source points (src). Source points “pump” a certain number of cubice meters per second into the model. To install source points, coordinates have to be given in Hydro-mt. An example is given below. In the example, there are 8 periods of 30 minutes for a total simulation of 4 hours.

```python
# x&y-locations in same coordinate reference system as the grid:
# In this example there are 3 waterdischarge points, they are noted like this.
x = [818876.48, 819476.572, 819691.68]
y = [9879309.01, 9879495.408, 9879424.72]

# add to Geopandas dataframe as needed by HydroMT
pnts = gpd.points_from_xy(x, y)
index = [1, 2, 3]  # NOTE that the index should start at one
bnd = gpd.GeoDataFrame(index=index, geometry=pnts, crs=sf.crs)

time = pd.date_range(
    start=utils.parse_datetime(sf.config["tstart"]),
    end=utils.parse_datetime(sf.config["tstop"]),
    periods=8,                                          # periods, because there are 4 hours each period is 30 minutes
)

# DISCHARGE INPUT
dis = np.array([ #was 150,26,24)
    [30, 1, 1],    #0:00
    [30, 1, 1],
    [30, 1, 1],
    [30, 1, 1],
    [420, 1, 1],
    [30, 1, 1],
    [30, 1, 1],
    [30, 1, 1]]
)
```

Figure 12: Hydro-mt code to install water source point for river discharge in Narok model. This configuration is for the 420 m^3/s flash flood.

At last there are observe points (obs). The water level at these points are registered during the runtime of the simulation. These points however are not put in the SFINCS model through coordinates in Hydro-mt. By building a vector layer in QGIS and adding these points on top of the prepared DEM, these points can be added to SFINCS. By downloading the vector layer from QGIS and loading the layer into Hydro-mt, SFINCS registers it as observatory points.

Chapter 3: Results

3.1 Cross-sections of Narok river

Several cross-sections of the river in Narok Various were surveyed. These surveys contain produced lists of coordinates and elevation data. The data were converted from coordinates to graphs of cross-sections with the Python script in Appendix A. This resulted in four cross sections for the sites in Narok. These four cross-sections are pictured below. Every measurement has its corresponding hydraulic geometry. Each element of the hydraulic geometry of the river will be discussed.

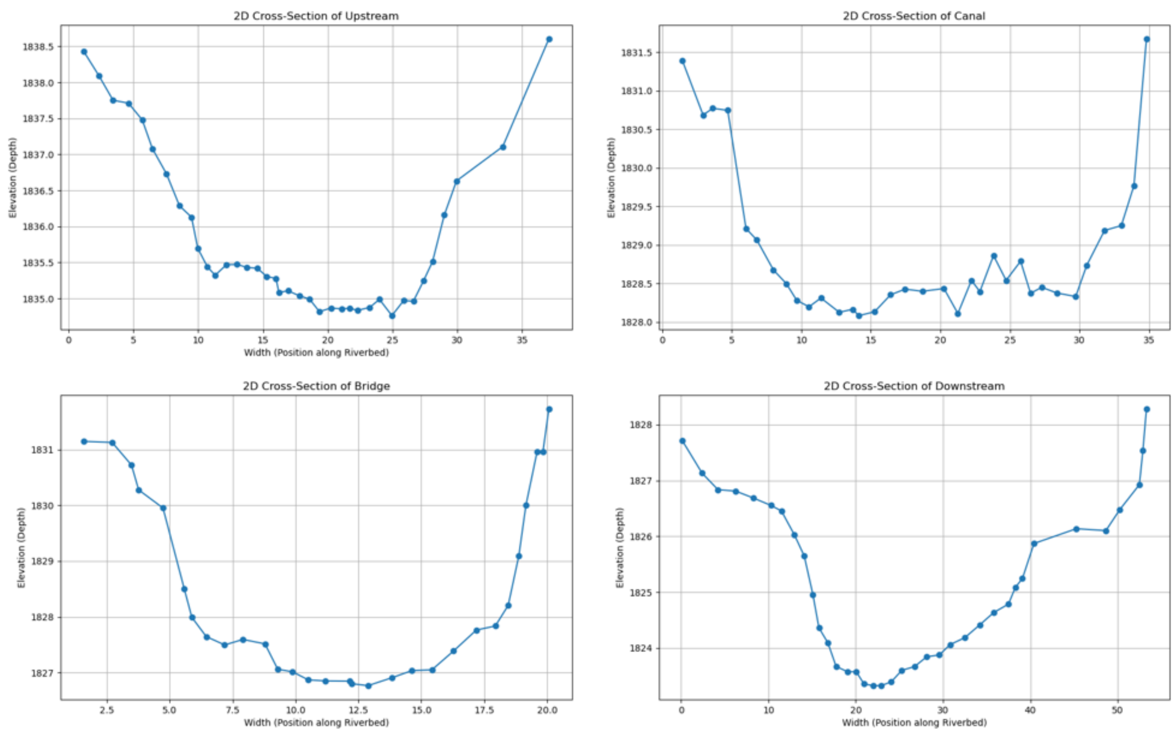


Figure 8: Four cross-sections of the Enkare-Narok river.

3.1.1 Width

For the calculation of the width, the total length between the first and last point of each cross-section was calculated. The width of these cross sections is quite important, as it helped with the calculation of the other element of the hydraulic geometry. This will be explained later in 3.1.2.

Width is also of importance as it was used for parts of the river in QGIS. The river was divided according to the measurement sites. Each part of the river was burned into the DEM in QGIS according using the measured widths. Each part of the river and the canals are given in the table below.

Table 1: Width of parts of the Narok river in the DEM and SFINCS simulation

Upstream	Canal	Bridge	Downstream	Big canal	Small canal
34 meter	37.9 meter	26.5 meter	56.3 meter	17.5 meter	6.6 meter

3.1.2 Average depth & hydraulic radius

The average depth is calculated with the maximum width of the cross sections and the surface of the cross sections. The total surface is divided by the maximum width of the cross section, which gives the average depth of the river. This average depth is used in the DEM in QGIS and SFINCS. For the Leopold parameters, the hydraulic radius is used as discussed in Chapter 2. Both are given in the table below.

Table 2: Average and Hydraulic radius of different measurement sites

	Upstream	Canal	Bridge	Downstream	Big canal	Small canal
Average depth	2.55 meter	2.94 meter	2.93 meter	2.50 meter	2.91 meter	2.05 meter
Hydraulic radius	2.44 meter	2.68 meter	2.41 meter	2.41 meter	-	-

With all the physical attributes of the river known, it was burned into the DEM. One important point in the river was the flood point. For a successful simulation of the floods in Narok, this point in the river needed to have the precise measurements corresponding to the measurement site of Canal. A picture of the cross-section of the flood point in the DEM is given below. The elevation of the riverbed is based on this cross section and the calculated slope of the river.

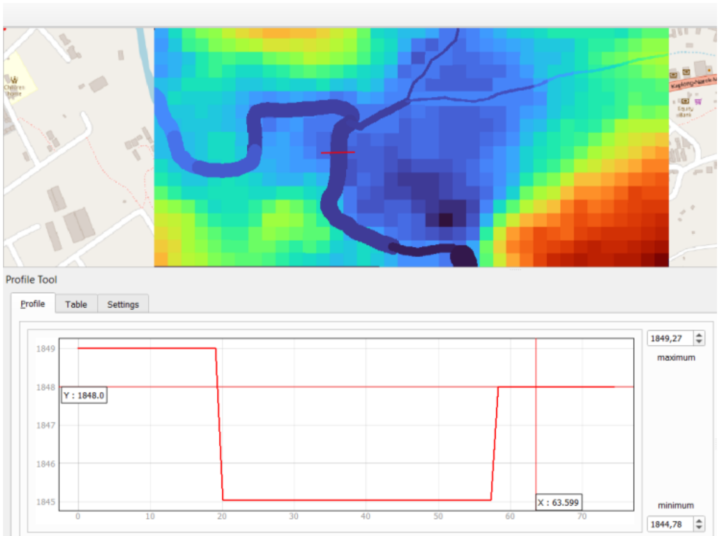


Figure 14: QGIS DEM of Narok city with elevation profile of riverbank which is the floodpoint.

3.1.3 Bed slope

The bed slope could be calculated on the basis of the elevation data. The slope is needed for the Manning equation to calculate the average velocity of the discharge in a bank full state. The bed elevations for the measurement sites are given below. The average bed slope was calculated to be 0.0055 m/m over a distance of 1950 meters.

Table 3: Riverbed elevation data at different sites

Upstream (m)	Canal (m)	Bridge (m)	Downstream (m)
1834.84	1829.46	1828.11	1824.06

3.2 Velocity

3.2.1 Velocity results

As described in Chapter 2, velocity tests were conducted at the measurement site of 'Upstream'. The results of these measurement tests are the time it took an orange to travel 10 meters in the river and are pictured below. The average surface velocity of the water in the middle of the river is 1.76 m/s. At the time of the measurements, the water level wat 1 meter above the river bed.

Table 4: Results velocity test at site Upstream

Test	1	2	3	4	5	6	7	8	9	10	Av	σ
t (s)	5,44	6,28	6	6,3	5,16	5,58	5,65	5,78	5,91	5,11	5,721	0,39
v (m/s)	1,84	1,59	1,67	1,59	1,94	1,79	1,77	1,73	1,69	1,96	1,76	0,12

3.2.2 Velocity profile

With this information of the maximum velocity at the surface, the average velocity needed to be calculated. A velocity profile was drawn based on the "Law of the Wall". The two unknown parameters where the roughness coefficient *z0 (m)* and *C (m/s)* with the shear stress coefficient. For *z0* an assumption was made based on sources to set it at 0.005 meter. With the calculated shear stress coefficient to match the maximum velocity, a coefficient of 0.075 (m/s) seems to be the best fit. This gave an average velocity of 1.42 m/s.

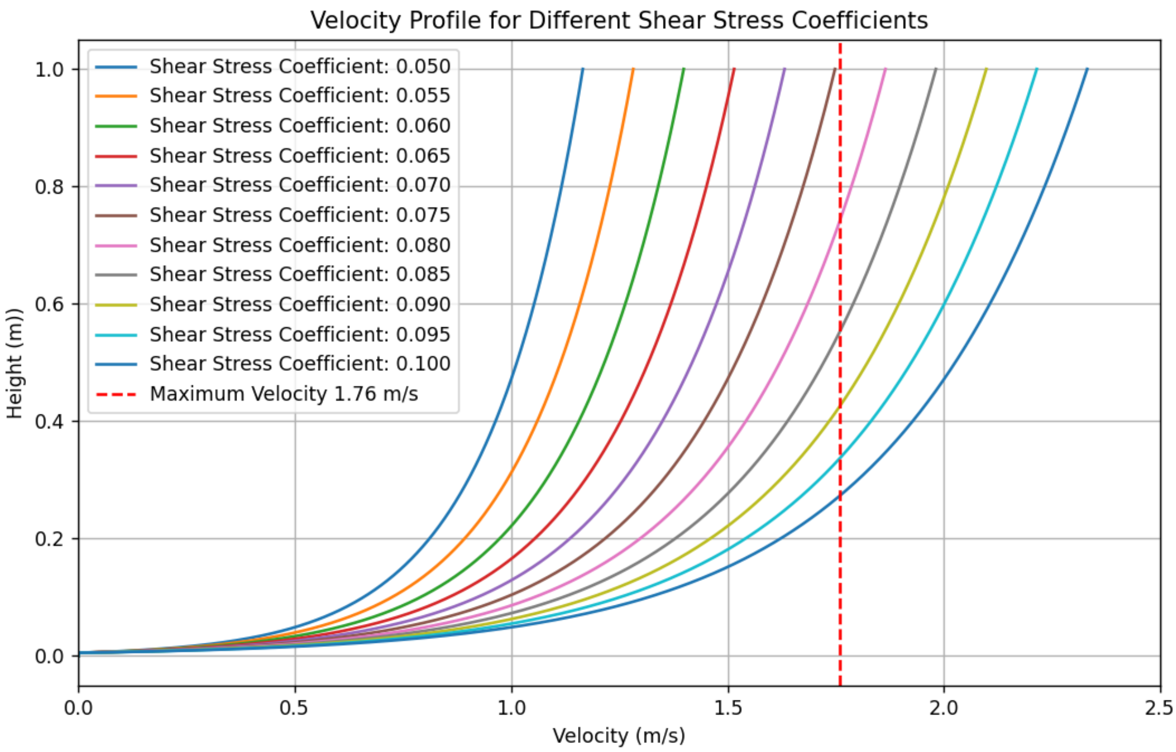


Figure 15: Velocity profile with average calculation over 1 meter water level

With the calculation of the velocity profile and average velocity, the Manning coefficient could be calculated for the river with the help of Mannings equation. The Manning coefficient was established to be 0.052 $m^{1/3}/s$. This was applied to the whole simulation and all the other discharge calculations.

3.3 Leopold parameters

As all parameters for the Manning equation are now known, they can be used to calculate discharges. The discharges are graphed against the hydraulic geometry parameters to find an exponential relation. The parameters of the exponential relation are used as Leopold's parameters and are used for verification. Leopold's parameters are shown in the table below and in the graphs. The mathematical requirement is fulfilled as both *a*c*k* and *b+f+m* are equal to 1.0. Leopolds parameters and the exponential relationship is used again to calculate the discharge of the river measurements. These discharges are described in the next paragraph.

Table 5: Results of Leopolds parameters from the field measurements of different sites

Leopold parameter	Multiplier	Power
Width	6.16 (a)	0.32 (b)
Hydraulic radius	0.28 (c)	0.39 (f)
Velocity	0.60 (k)	0.27 (m)

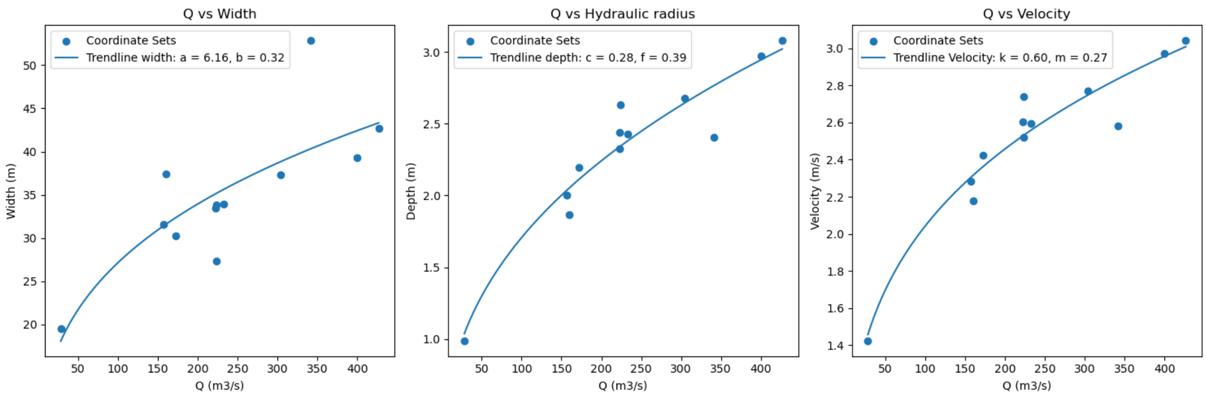


Figure 16: Exponential graph of the relation between the hydraulic geometry parameters vs the assumed discharge

3.4 SFINCS results

3.4.1 Leopolds discharges

Below is a total overview of the discharges given from Leopold's method and Manning for the various sites. For the four natural sites, the "Average" discharges of Leopold's method will be used in SFINCS. The natural maximum capacity will be tested to see if it will flood in the simulation. To test the bridge capacity in SFINCS the Manning discharge is assumed to be the maximum capacity, as it is not part of the natural river. This maximum discharge capacity below the bridge is also tested in SFINCS. The two outliers, the Width discharge of the Bridge and Downstream site will be discussed further in the discussion in Chapter 4.

Table 6: Discharges given according to the various formulas from Leopold and Manning. The bold numbers are used to test the river capacity in SFINCS.

Site	Width (m^3/s)	Depth (m^3/s)	Velocity (m^3/s)	Average (m^3/s)	Manning (m^3/s)
Low	33	26	26	**29**	28
Upstream	180	258	258	**232**	223
Canal	187	254	254	**232**	233
Bridge	38	286	286	203	**166**
Downstream	753	249	249	**417**	341

3.4.2 SFINCS simulations

For the simulations in SFINCS the highlighted discharges in Table 6 are chosen for verification. Constant discharges from 30 to 160 m^3/s were simulated and did not result in floods from the river in Narok. This was with a constant discharge for the 4 hours of the simulation. The constant water level and balance of the river will be shown in 3.4.2.1.

Flash floods are the main concern for the situation in Narok. For the flash flood simulation the base river discharge was set to 30 m^3/s. The simulation was a 4 hour simulation divided in 8 parts of half an hour. There was an half hour high discharge simulated from 02:00 to 02:30 in the simulation. The high discharge started from 170 m^3/s up to 230 m^3/s in steps of 10 m^3/s. For every one of these scenarios there was a flood. This was done up to 230 m^3/s because it is the maximum river discharge of the river upstream of Narok. Also a simulation was done with 420 m^3/s, as this was the maximum discharge of Downstream. This is both the discharge of the river and the canals combined, and these discharges would affect the size of the flood.

3.4.2.1 Waterlevel

To research the exact moment the river went out of its bank, the water level was measured in some parts of the river during the simulation. This was done with observatory point (OBS) in SFINCS. These points monitor the water level during the simulation. The given floodpoint is 2.96 meters above the riverbed, near OBS 2. Below are given the water levels of OBS 2 during constant water levels of 30 and 160 m^3/s and a flash flood with 230 m^3/s. During the flash flood, it is clearly shown that the water level rises rapidly until exceeds the top of the river bed. The water level exceeds the top of the the river bed near the end of the flash flood. As soon as the flash flood is over it the level reduces to pre-flash flood water level. All water flows away either through the river or the floodplains.

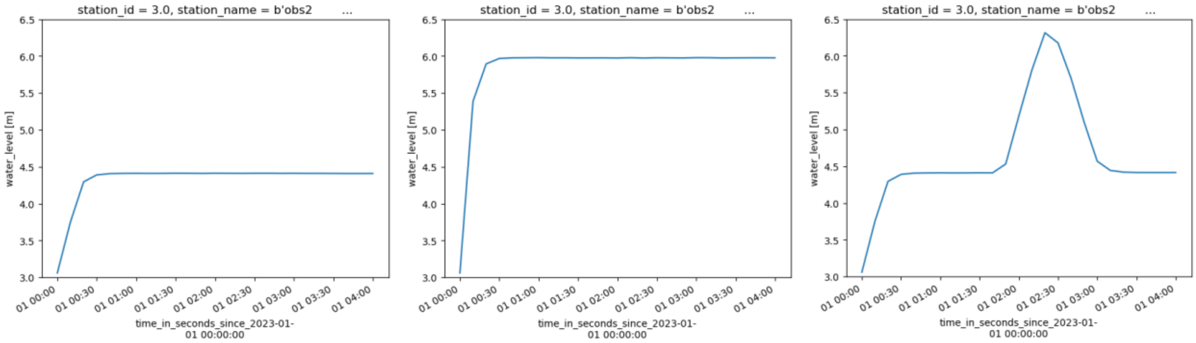


Figure 17: From left to right, waterlevel at OBS2: constant discharge of 30 m3/s, constant discharge of 160 m3/s and a flash flood with 230 m3/s.

To see the influence of the biggest possible flood on the water level, all 6 OBS are pictured below with a flash flood of 420 m^3/s. No water was flowing into the canals during these simulations as the discharge of 420 m^3/s could not be carried by the relatively small canals. However the canals flooded as well as the water level rose to such a high level they could not contain all the water.

The graphs show an overview of the water levels again. During the rise in the graphs of the 420 m^3/s flash flood it can be noted the water is too much for the river itself. The water tries to flow every way and even rises in the canals. When the water reaches the flood point, the rise of the water level flattens out. From OBS2 the peak of the water level is lower.

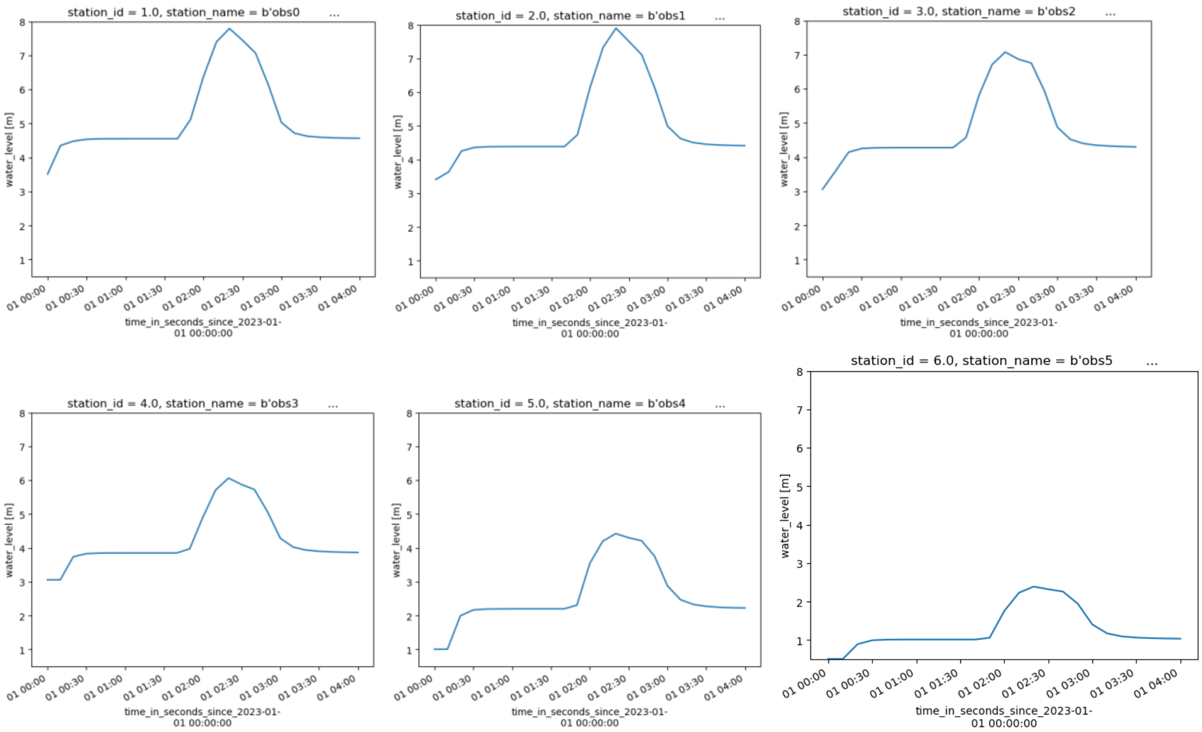


Figure 18: OBS 0 till 5 with the water level of a flash flood of 420 m^3/s.

3.4.2.2 Flood velocity

The speed of a flash flood should also be taken into account. Each square in SFINCS is 30 meter by 30 meter. In the figure below are 6 steps represented of the 230 m3/s flash flood. The flood starts at 02:15 of the simulation in the middle map of the top row. In five minutes the flood has spread over almost 18000 square meters. In the bottom row the water flood spreads further and the water level rises in the already flooded area. After 20 minutes the peak of the flood is over, yet the water still remains outside the river bank and has no mean to flow back in to the river.

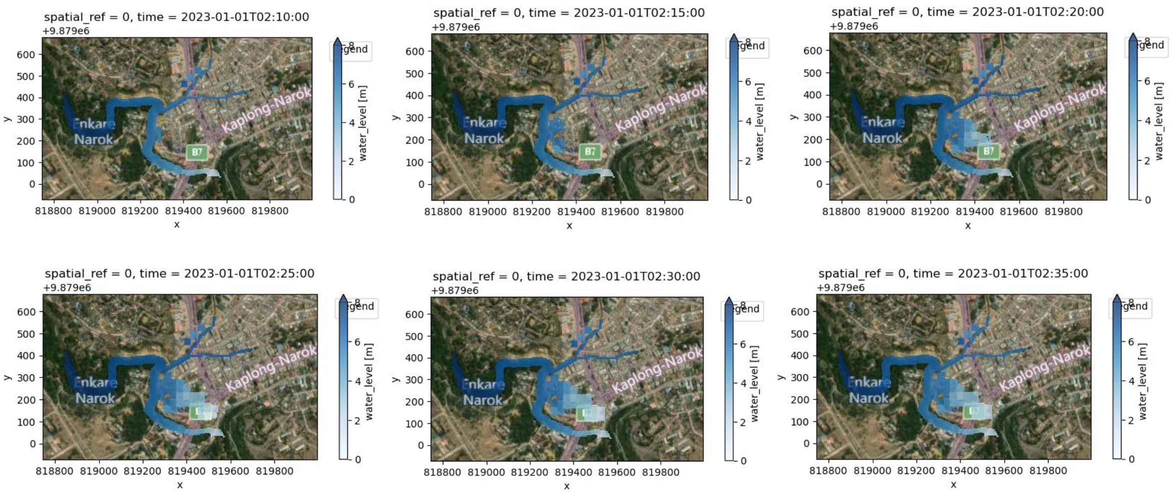


Figure 19: Six SFINCS maps to represent the speed of the flash flood. Every map represent 5 minutes from the flash flood with a discharge of 230 m^3/s.

3.4.2.3 Flood size

Below are maps of the floods at the height of the peak from the 230 m^3/s and 420 m^3/s flash floods. These are shown to see the difference in areas of the floods. It is noticed that with this size of flood of the Downstream river, the water level rises so high, even the canals flood upstream of the confluence, outside the estimated flood area due to backwater effects. The 230 m^3/s flash flood stays in the estimated flood area.

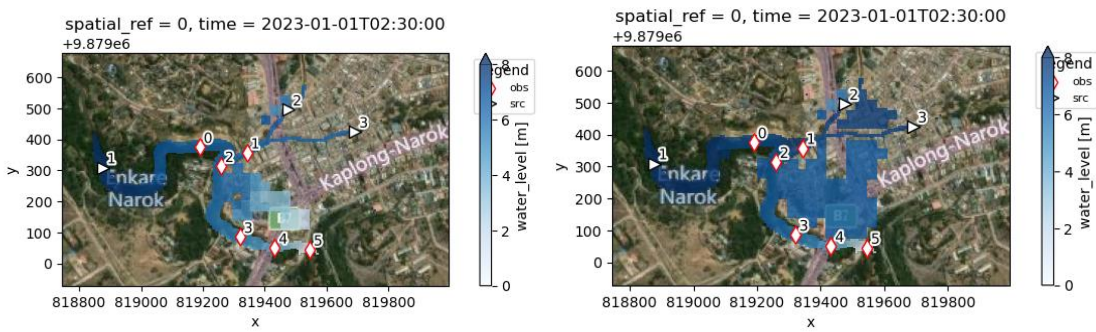


Figure 20: On the left is the Narok city with a flash flood of 230 m^3/s, on the right it is 420 m^3/s.

Chapter 4: Conclusion & discussion

The goal of the research was to develop a method to calculate the river discharge based on hydraulic geometry with Leopold's theory and some simple field measurements. In the end a tool was created which uses Leopold's theory as a verification for discharges calculated by Manning's equation. It provides a first step in a Rapid Hydraulic Assessment tool for data scarce areas.

With the extension to SFINCS, the calculations could be tested through simulation in the SFINCS program. The measurements of the river were reconstructed in the SFINCS program and various amounts of water were forced through the river to test the maximum capacity. The simulation confirmed the maximum discharge below the bridge and the maximum capacity of the river and canals. The flood plain was also roughly similar to floods from the past.

The development of this tool is based on one area, Narok town, with multiple measurement sites, multiple days and multiple measurements. However, the application of the tool on multiple locations could test its real value. Eventually, we used eleven detailed measurements of cross sections for the final tool, as well as surface velocity tests to determine the Manning's roughness coefficient. An assumed logarithmic velocity profile based on the Von Karman theory, led to an eventual Manning coefficient by applying Manning's equation to one cross section of the measured site during the velocity tests taking into account the slope of the streambed.

Finally by graphing the assumed discharges from Manning's equation against the hydraulic geometry of the full bank river, it was possible to use Leopold's theory, which gave accurate results for two of the three parameters. In the graphs of Velocity and Hydraulic radius, a coefficient of determination (R^2) of over 0.8 was reached for the parameters for depth and velocity. However, the coefficient of determination for the parameters associated with the width was just over 0.5. Where the average discharges of Leopold's formulas were often similar to Manning's discharges, the discharge based on the width always differed significantly. It shows that the Width parameters show a high sensitivity, which makes it hard to use this for the prediction of river discharges. This becomes especially clear in the results of the Downstream site were the river is relatively wide. The width at this location is altered due to the fact it is an old crossing. On this spot, the assumed bank full discharge based on Leopold's parameters for Width are different from the discharge as calculated with Manning's equation. It is safe to assume that the parameter Width is the first to change rapidly with different quantities of river discharge. The parameters Velocity and Depth have a more consistent relationship with the river discharge.

The method of applying Manning's equation for an assumed discharge of a bank full river and to verify it with Leopolds theorem is in its first steps. With the help of multiple measurements of a river at various measurements sites, a correct Manning coefficient can be determined, which, together with the slope of the river bed, can be used to determine the natural maximum discharge. Where other data is not available this could help build Flood Early Warning Systems and provide better design parameters for infrastructure such as bridges.

The Rapid Hydraulic Assessment tool is split up into two parts. One is to determine the discharge of the river based on measured cross section with coordinates. The second part is the use of Hydro-mt and SFINCS to simulate the floods with the assumed discharges of the bank full state of the river. In the instance of Narok, the floods were realistically simulated with verification of the local population. The tool comes with an installation package for Hydro-mt and SFINCS. The tool is still in an early phase, as it is a compound of multiple programs with multiple installations and gathering of various forms of data. It is a rough first step in the development of the estimation of river discharge in data scarce areas with minimal equipment. However, with the new usage of Leopold's method to verify bank full discharge of Manning, it is a step in the right direction. With the usage of the tool in other areas, it could be optimised and Leopold's method could be applied in the verification of bank full assumed discharges by Manning in other places as well.

References

Alsdorf, D., & Lettenmaier, D. P. (2003). Tracking Fresh Water from Space. *Science*, *301*(5639), 1491–1494. https://doi.org/10.1126/science.1089802

Ashmore, P., & Sauks, E. (2006). Prediction of discharge from water surface width in a braided river with implications for at-a-station hydraulic geometry. *Water Resources Research*, *42*(3). https://doi.org/10.1029/2005wr003993

Bjerklie, D. M., Dingman, S., Vörösmarty, C. J., Bolster, C. H., & Congalton, R. G. (2003). Evaluating the potential for measuring river discharge from space. *Journal of Hydrology*, *278*(1–4), 17–38. https://doi.org/10.1016/s0022-1694(03)00129-x

Bösmeier, A. S., Himmelsbach, I., & Seeger, S. (2022). Reliability of flood marks and practical relevance for flood hazard assessment in southwestern Germany. Natural Hazards and Earth System Sciences, 22(9), 2963–2979. https://doi.org/10.5194/nhess-22-2963-2022

Dingman, S. (2007). Analytical derivation of at-a-station hydraulic–geometry relations. *Journal of Hydrology*, *334*(1–2), 17–27. https://doi.org/10.1016/j.jhydrol.2006.09.021

Gleason, C. J., & Smith, L. C. (2014). Toward global mapping of river discharge using satellite images and at-many-stations hydraulic geometry. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(13), 4788–4791. https://doi.org/10.1073/pnas.1317606111

Gleason, C. J., Smith, L. C., & Lee, J. Y. (2014). Retrieval of river discharge solely from satellite imagery and at-many-stations hydraulic geometry: Sensitivity to river form and optimization parameters. *Water Resources Research*, *50*(12), 9604–9619. https://doi.org/10.1002/2014wr016109

Gleason, C. J., & Ji-Da, W. (2015). Theoretical basis for at-many-stations hydraulic geometry. *Geophysical Research Letters*, *42*(17), 7107–7114. https://doi.org/10.1002/2015gl064935

Grison, F., De Almeida Mota, A., & Kobiyama, M. (2021). Testing the Leopold-Maddock and the Dingman hydraulic geometry hypotheses with detailed measurements in a small river. *Hydrological Sciences Journal*, *66*(8), 1372–1382. https://doi.org/10.1080/02626667.2021.1925285

Hoedjes, J. C. B., Kooiman, A., Maathuis, B. H. P., Said, M. Y., Becht, R., Limo, A., Mumo, M., Nduhiu-Mathenge, J., Shaka, A., & Su, B. (2014). A conceptual flash flood early warning system for Africa, based on terrestrial microwave links and flash flood guidance. ISPRS International Journal of Geo-Information, 3(2), 584–598. https://doi.org/10.3390/ijgi3020584

Lawrence, D. S. (2007). Analytical derivation of at-a-station hydraulic-geometry relations. Journal of Hydrology, 334(1–2), 17–27. https://doi.org/10.1016/j.jhydrol.2006.09.021

Leijnse, T. (2023). SFINCS Documentation Release 2.0.2_Blockhaus INTRODUCTION.

Leopold, L. B., & Maddock, T. (1953). The hydraulic geometry of stream channels and some physiographic implications. *U.S. Geological Survey Professional Papers/U.S. Geological Survey Professional Paper*. https://doi.org/10.3133/pp252

Rao, K. H. V. D., Shravya, A., & Dadhwal, V. K. (2020). A novel method of satellite based river discharge estimation using river hydraulic geometry through genetic algorithm technique. *Journal of Hydrology*, *589*, 125361. https://doi.org/10.1016/j.jhydrol.2020.125361

Smart, G., Aberle, J., Duncan, M., & Walsh, J. (2004). Measurement and analysis of alluvial bed roughness. Journal of Hydraulic Research, 42(3), 227–237. https://doi.org/10.1080/00221686.2004.9728388

Smith, L. C., & Pavelsky, T. M. (2008). Estimation of river discharge, propagation speed, and hydraulic geometry from space: Lena River, Siberia. *Water Resources Research*, *44*(3). https://doi.org/10.1029/2007wr006133

Srinivasa Rao, D., Kumar Bammidi, A., Rao, S. D., & Kumar, A. B. (2019). A survey of flood disaster monitoring and controlling mechanisms with focus on structural measures. In Disaster Advances Vol (Vol. 12, Issue 3). https://www.researchgate.net/publication/331686687

Williams, G. P. (1978). Bank-full discharge of rivers. *Water Resources Research*, *14*(6), 1141–1154. https://doi.org/10.1029/wr014i006p01141

Xu, K., Zhang, J., Watanabe, M., & Sun, C. (2004). Estimating river discharge from very high-resolution satellite data: a case study in the Yangtze River, China. *Hydrological Processes*, *18*(10), 1927–1939. https://doi.org/10.1002/hyp.1458

Yan, K., Pappenberger, F., Umer, Y. M., Solomatine, D. P., & Di Baldassarre, G. (2014). Regional Versus Physically-Based Methods For Flood Inundation Modelling In Data Scarce Areas: An Application To The Blue Nile. https://academicworks.cuny.edu/cc_conf_hic/111Discoveradditionalworksat:https://academicworks.cuny.edu

Zhang, J., Xu, K., Watanabe, M., Yang, Y., & Chen, X. (2004). Estimation of river discharge from non-trapezoidal open channel using QuickBird-2 satellite imagery/Utilisation des images satellites de Quickbird-2 pour le calcul des débits fluviaux en chenaux ouverts non-trapézoïdaux. *Hydrological Sciences Journal*, *49*(2). https://doi.org/10.1623/hysj.49.2.247.34831

Zimmermann, A., & Church, M. (2001). Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel. In Geomorfologie (Vol. 40). www.elsevier.comrlocatergeomorph

A: Python code coordinates

```
import matplotlib.pyplot as plt
import numpy as np
import math
from scipy.optimize import curve_fit
import sys
# Make a list of the coordinates

coordinate_sets = [
    coords_rivercanal2,
    coords_rivercanal1,
    coords_rivercanal21,
    coords_rivercanal23,
    coords_rivercanal24,
    coords_riverbegin1,
    coords_riverbegin2,
    coords_riverbegin3,
    coords_riverbegin4,
    coords_riverbegin22,
    coords_riverspeed,
    coords_riverdown1
]

# Copy the list above and set them as names here to know which discharge
belongs to which coordinate set
name_sets = [
    "coords_rivercanal2",
    "coords_rivercanal1",
    "coords_rivercanal21",
    "coords_rivercanal23",
    "coords_rivercanal24",
    "coords_riverbegin1",
    "coords_riverbegin2",
    "coords_riverbegin3",
    "coords_riverbegin4",
    "coords_riverbegin22",
    "coords_riverspeed",
    "coords_riverdown1"
]


# This is the code for converting coordinates to measurements

def haversine(lat1, lon1, elev1, lat2, lon2, elev2):
    # Radius of the Earth in meters
    R = 6371000  # approximately 6,371 kilometers
```

```
    # Convert latitude and longitude from degrees to radians
    lat1, lon1, lat2, lon2 = map(math.radians, [lat1, lon1, lat2, lon2])

    # Differences in latitude and longitude
    dlat = lat2 - lat1
    dlon = lon2 - lon1

    # Haversine formula for distance
    a = (math.sin(dlat / 2) ** 2) + math.cos(lat1) * math.cos(lat2) *
(math.sin(dlon / 2) ** 2)
    c = 2 * math.atan2(math.sqrt(a), math.sqrt(1 - a))
    distance = R * c

    return distance


def haversine2(lat1, lon1, elev1, lat2, lon2, elev2):
    # Radius of the Earth in meters
    R = 6371000  # approximately 6,371 kilometers

    # Convert latitude and longitude from degrees to radians
    lat1, lon1, lat2, lon2 = map(math.radians, [lat1, lon1, lat2, lon2])

    # Differences in latitude and longitude
    dlat = lat2 - lat1
    dlon = lon2 - lon1

    # Haversine formula for distance
    a = (math.sin(dlat / 2) ** 2) + math.cos(lat1) * math.cos(lat2) *
(math.sin(dlon / 2) ** 2)
    c = 2 * math.atan2(math.sqrt(a), math.sqrt(1 - a))
    distance = R * c

    #Calculate the 3D distance, considering elevation
    distance_3d = math.sqrt(distance**2 + (elev2 - elev1)**2)

    return distance_3d


# Calculate the surface area enclosed by the coordinates
def calculate_surface_area(coords):
    num_coords = len(coords)
    if num_coords < 3:
        return 0.0, 0.0  # Not enough coordinates to form a shape

    total_area = 0.0
    total_width = 0.0
    river_area = 0.0
```

```
    bottom_area = 0.0
    wetted_perimeter_total = 0.0
    hydraulic_depth = 0.0

    # Extract elevation values from the list of coordinates
    elevations = [elev for _, _, elev in coords]

    # Sort the elevations in descending order
    sorted_elevations = sorted(elevations, reverse=True)

    # Find the second-highest elevation
    second_highest_elevation = sorted_elevations[1]

    for i in range(num_coords):
        j = (i + 1) % num_coords

        lat1, lon1, elev1 = coords[i]
        lat2, lon2, elev2 = coords[j]

        # Calculate the width only if we are not wrapping around (last point
handled separately)
        if i == num_coords - 1:
            break

        width = haversine(lat1, lon1, elev1, lat2, lon2, elev2)
        total_width += width

        height = abs(elev2 - elev1)
        height2 = abs(second_highest_elevation - elev1)
        bottom_area = (width * height) / 2.0
        river_area = height2 * width
        total_area += bottom_area + river_area

        wetted_perimeter = haversine2(lat1, lon1, elev1, lat2, lon2, elev2)
        wetted_perimeter_total += wetted_perimeter


    mean_depth = total_area / total_width

    hydraulic_depth = total_area / wetted_perimeter_total

    return abs(total_area), abs(mean_depth), total_width,
wetted_perimeter_total, abs(hydraulic_depth)
```

```
# Here is the code for converting the measurements to discharge

def calculate_velocity(slope, width, depth, Manning_coefficient,
wetted_perimeter):

    # Manning's equation: v = ((1/n) * R^(2/3) * S^(1/2)
     # Hydraulic radius (A/P)
    hydraulic_radius =  (width * depth) / wetted_perimeter

    velocity = (1 / ( Manning_coefficient)) * (hydraulic_radius**(2/3) *
(slope)**(1/2))

    return velocity


def calculate_discharge(width, depth, slope, Manning_coefficient,
wetted_perimeter):
    g = 9.81  # Acceleration due to gravity (m/s^2)

    # Manning's equation: Q = (1/n) * A * R^(2/3) * S^(1/2)
    hydraulic_radius = (width * depth) / wetted_perimeter  # Hydraulic radius
(A/P)
    discharge = (1 / Manning_coefficient) * (width * depth) *
hydraulic_radius**(2/3) * (slope)**(1/2)

    return discharge

def calculate_Leopold(width, depth, slope, Manning_coefficient,
wetted_perimeter, hydraulic_depth, a, c, k, b, f, m):

    #First calculate the velocity through Manning equation
    velocity = calculate_velocity(slope, width, depth, Manning_coefficient,
wetted_perimeter)

    # Next is calculating the discharge based on the realtions
    # relations are W = a * Q ** b rewrite to Q = (W / a) ** (1/b)
    # w = a*Q**b, d = c*Q**f, v = k*Q**m
    # b =0.5, f = 0.4, m = 0.1, for average annual downstream rivers
    #for floods and measured it is 0.5 0.1 and 0.3

    discharge_width = ((1/a) * width) ** (1/b)
    discharge_depth = ((1/c)*(hydraulic_depth)) ** (1/f)
    discharge_velocity = ((1/k)*(velocity)) ** (1/m)

    average_discharge = (discharge_width + discharge_depth +
discharge_velocity) / 3

    return discharge_width, discharge_depth, discharge_velocity,
average_discharge
```

B: Step to Step guide for measurements

This is a step to step guide for the installation and use of the hydraulic assessment tool for river flood discharge in data scarce areas. First there is a list of things you need minimal:

- Laptop
- Android phone
- Ardusimple set with a Base and Rover
- u-blox (installed on laptop)
- SW Maps (installed on phone)
- Tripod
- Measuring rod
- Tape

Connecting u-blox with Ardusimple set

1. Connect the Base with your laptop through a micro-usb cable. Connect the antenna and Bluetooth receiver to the Base as well.
2. Duct tape the antenna on top of the tripod to make sure it does not move. Do not interfere with the receiving part of the antenna.
3. In u-blox, Click on R*eceiver* in the top left corner of your screen and *Connection* after. A menu with available COM ports will open. Select the port with the connected Base.
4. Go to View and select *Messages View*
5. In *Messages*, look for *UBX* and click on *CFG (Config)*. Select *Time Mode 3*, here you put your minimum calibration time and minimum calibration distance. Both configurations need to be fulfilled before you can actually use it, so for distance you put 2 meters and for time 1 hour. This is to ensure that you can use it after 1 hour of calibration. Hit *Send* to start
6. Now below *CFG (Config)* go to *CFG (Configuration)*. Click *Select all* and hit *Save* and *Send*.
7. Now wait for 1 hour for the calibration of your base with available satellites.
8. Write down the coordinates and elevation in the top right corner of the Base. You will not need an hour long calibration next time you are back.

Connecting your phone with Ardusimple set

1. Open Installation on your Android phone
2. Go all the way to the bottom and select *Developer Options*.
3. Go all the way to the bottom to location, open *App for fake location* and select SW Maps
4. Turn on *Fully apply GNSS-measurements*
5. Connect your phone through a micro-usb cable to the Rover.
6. Turn off the *Location* of your phone
7. Open *SW Maps*
8. Start a new project
9. Open the menu and select *USB Serial GNSS*
10. Install the Instrument height of your measurement pole where the rover will be on top of.
11. Click *Connect*

Taking measurements

1. Make sure all the parts of your Base of the Ardusimple set are connected and u-blox is calibrated.
2. Duct tape the antenna of the Rover on top of your measuring pole. Duct tape the Rover slightly below it while connected.
3. Now follow the steps of **Connecting your phone with Ardusimple set** from step 7.
4. Stand on your starter position on the river bed. Place the measurement pole with the Rover straight and next to you
5. Look at your phone. Select the pencil in the bottom right corner and select *Record using GPS*.
6. Look at *Fix type.* If the status says *RTX Fix* it means all components are calibrated and you have the most accurate position.
7. Turn on *Averaging*.
8. Click on the *plus point* symbol in the bottom right corner, wait till you have at least 50 points and turn it off.
9. Now take one step in direction of the other riverbank, place the measurement pole next to you again and stand still.
10. Repeat step 5 to 9 till your at the other river bank.

Preparing data for Python

1. Open *SW Maps*
2. Open your project
3. Open the menu, go down till you see *Share*
4. Share in XLS format and export your layer or all layers you want to use.
5. Send it to your own email.
6. Open the file in Excel
7. Copy the *Geometry* column and paste it next to all the data where you can see it clearly.
8. Select the new column, click *Find and select* and select *Replace*.
9. Replace all the *POINT Z* with nothing
10. Replace all the *,* with .
11. Replace all the *spaces* with *space,*
12. Replace) with),
13. Copy the column to python.