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Flood Risk Assessment Isiolo River Basin, Kenya

Feasibility of the SLAMDAM in the Isiolo River Basin using the FIS Tool

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Preface

This report is part of the master study program of Civil Engineering at Delft University of Technology, defined as a Civil Engineering Consultancy Project. This project combines several disciplines for a civil engineering related project. For this project, the disciplines are Water Management, Geo-Engineering and Construction Management and Engineering.

The project has been set up in collaboration with two Dutch companies, namely Nelen & Schuurmans and Zephyr Consulting and the project has been conducted in Kenya where we were stationed in Nairobi and Nanyuki for a total duration of 8 weeks. Thanks to Nelen & Schuurmans, we were able to use valuable tools such as the Flood Intelligence Service (FIS) Tool and 3Di to consult in the best possible way. And thanks to Zephyr Consulting, we were able to try out the innovative SLAMDAM: a movable, modular dam which can be used as a flood mitigation measure or for water retention or storage.

Other partners during the project to whom we are very grateful are the Water Resources Authority (WRA), Netherlands Development Organisation (SNV) Kenya, the embassy of the Kingdom of the Netherlands, the National Drought Management Authority (NDMA), Trans-African Hydro-Meteorological Observatory (TAHMO), WRA ENN basin area Regional Office, WRA Isiolo, Water Resources Users Association (WRUA) Isiolo, and the Centre for Training and Integrated Research in ASAL Development (CETRAD). Thanks to all these parties we were able to gather a lot of knowledge, data, and contacts.
The organisations which provided funding we would like to thank are FAST (Delft University Fund), FIS Grant, and Global Initiative. They have contributed to the fact that we were able to perform our research in Kenya.

Of course we also want to thank our supervisors Nick van de Giesen, Johan Ninan, and Bram van den Eijnden from the TU Delft, and Joost van der Hammen, Stijn Muntjewerff, and Omar Saleh from Nelen & Schuurmans and Zephyr Consulting. Lastly, we would like to thank Lillian Kalela, our local supervisor from Zephyr Consulting, who enabled us to have such a good and educational experience in Kenya, both study and cultural related.

Nelen & Schuurmans

ZEPHYR CONSULTING & TRADING

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Abstract

This report will provide a flood risk assessment of the Isiolo River Basin. This includes a study of the current flood risk management in Kenya and in this basin in particular because the need for proper flood management is urgent in Kenya: various climate studies predict an increase in rainfall and an increase in flood risk as a result of the effects of climate change.

Current flood risk management is inadequate, Kenya has defined 21 flood-prone areas whereof one of them is Isiolo Town. Isiolo Town is located in the ENN basin which is, relatively, the most prone to the effects of climate change compared to the other basins. Furthermore, the ENN basin currently has the highest poverty rate and avoidance of further enlargement in poverty rate is important, so there is a need to mitigate flood risks. Since Isiolo Town is located in the Isiolo River Basin, this basin has been chosen for an in-depth study.

The Isiolo River Basin is an Arid Semi-Arid Land region which is often prone to flash floods. Isiolo Town is a flat area located downstream of mountainous area, the rain which falls upstream flows fast downstream and converges into town, often resulting in inundation. Many hazards, both natural and others, are increasing the flood risk in the basin and specifically Isiolo Town.

This flood risk demands flood risk mitigation measures. One possible measure is the SLAMDAM. The SLAMDAM is a movable water-filled flood-barrier. One dam has a length of 5 meters and a height of 1 meter and the dams can be connected to a desired length. The water stored in the dam can be used afterwards for irrigation or other uses.
To recommend effective areas to implement the SLAMDAM, 3Di and the FIS Tool are used. 3Di is a hydrodynamic model and it creates flood maps for different rain events. These flood maps are used as input for the FIS Tool. The FIS Tool calculates the benefits for deploying the SLAMDAM at a certain location for a particular length. The locations which result in the highest benefit are recommended to deploy the SLAMDAM in case of particular rain events. However, a site visit is required to see whether the modelled situation aligns with the real-life situation and to see whether boundary conditions are met.
The SLAMDAM is also compared to other flood risk mitigation measures. Some were analysed using the FIS Tool, whereas others are evaluated based on five self-formulated ranking criteria. These criteria form the base of a scoring matrix where each relevant mitigation measure is scored on.

The performed research has shown the SLAMDAM to rank the best compared to other mitigation measures, both when using the scoring matrix and when using the FIS Tool. However, it is highly recommended to use the SLAMDAM in combination with a Flood Early Warning System. In this way the community downstream can be warned in time to deploy the SLAMDAM. The FIS Tool is found to be especially valuable in finding proper locations for deployment and the dam can be stored close to these locations, enabling fast deployment of the dam in case of need.

Contents

List of Abbreviations

Abbreviations	Definition
ABM	Account Based Marketing
AM	Annual Maxima
API	Application Programming Interface
ASAL	Arid and Semi Arid Land
a.s.l.	above sea level
BWRC	Basin Water Resources Committee
CAAC	Catchment Advisory Committees
CETRAD	Centre for Training and integrated Research in ASAL Development
CIDP	County Integrated Development Plan
DAC	Development Assistance Committee
DEM	Digital Elevation Map
ENN	Ewaso Ng'iro North
EPDM	Ethylene Propylene Diene Monomer
ESRI	Environmental Systems Research Institute
FCDC	Frontier Counties Development Council
FEWS	Flood Early Warning System
FIS	Flood Intelligence Service
GCP	Gross Country Product
GDU	Governor's Delivery Unit
GDP	Gross Domestic Product
HRU	Hydrological Response Unit
ICPAC	IGAD Climate Prediction and Application Centre
IGAD	Intergovernmental Authority Development
JICA	Japan International Cooperation Agency
KEWI	Kenya Water Institute
KMD	Kenya Meteorological Department
KWTA	Kenya Water Towers Agency
LAPSSET	Lamu Port South Sudan Ethiopia Transport Corridor
LISTEN	Laikipia Isiolo Samburu Transforming the Environment through Nexus
LVN	Lake Victoria North
LVS	Lake Victoria South
MAP	Mean Annual Precipitation
NAP	Kenya National Adaption Plan
NDMA	National Drought Management Authority
NDMU	National Disaster Management Unit
NDOC	National Disaster Operation Centre
NEMA	National Environment Management Authority
NWHSA	National Water Harvesting and Storage Authority
NWMP	National Water Master Plan
OECD	Organisation for Economic Cooperation and Development
POT	Peak Over Threshold
QGIS	Quantum Topographic Information System
RV	Rift Valley
SCMP	Sub-Catchment Management Plan
SNV	Stichting Nederlandse Vrijwillegers (Dutch Development Organisation
SRTM	Shuttle Radar Topography Mission
SuDs	Sustainable Drainage system
SUED	Sustainable Urban Economic Development
TAHMO	Trans-African Hydro-Meteorological Observatory
UTM	Universal Transverse Mercator
WASREB	Water Services Regulatory Board
WDC	Water Resource Users Association Development Cycle
WRA	Water Resources Authority
WRI	World Research Institute
WRMA	Water Resource Management Authority
WRUA	Water Resources Users Association
WSP	Water Service Providers
WSTF	Water Sector Trust Fund
WWDA	Water Works Development Agencies

Chapter 1

Introduction

1.1 Context and relevance of the project

Kenya is a country located in North East Africa that is just as other countries in the world subject to the effects of climate change. In Kenya, climate change is a threat to the water resources. The water resources of Kenya are also prone to the threat of many other issues, whereof one of them is inadequate flood management (Aurecon AMEI Limited, 2020b).

Overall most rainfall in Kenya occurs during April and May, referred to as the 'long rains'. The so-called 'short rains' occur from September to November. Due to climate change, the intensity and frequency of extreme events is expected to increase. This may result in an increased frequency of floods which is accompanied with damage related to people's health, economics, conflict, and infrastructure (Aurecon AMEI Limited, 2020b). Therefore, an adequate flood risk management is of even greater importance in the future.

Kenya is divided into six basins, whereof one of them is the Ewaso Ng'iro North (ENN) basin. The ENN basin is one of the drier parts of Kenya, with a mean annual precipitation (MAP) of 377 mm. This is lower than the mean annual precipitation of the whole of Kenya, which is 595 mm. However, climate change will possibly effect this ENN basin the most compared to all other basins in Kenya. Over the period 2018-2050, the percentage change in MAP is expected to be the highest, namely +10.9% (Aurecon AMEI Limited, 2020b). Variability as well as intensity of rainfall are expected to increase during both rainy seasons. Additionally, a climate analysis on flow indicated that just as with rainfall, the flow is expected to increase during both rainy seasons. The percentage of change of surface water due to climate change is +9.0% for this particular basin (Aurecon AMEI Limited, 2020b). This is just as for rainfall the biggest change in percentage compared to other basins in Kenya. Next to this, the groundwater potential for this basin will change the most compared to the other basins: +11.6% in the same period 2018-2050 (Aurecon AMEI Limited, 2020b).

With its high expected percentage changes in rainfall, surface water, and groundwater potential as a result of climate change, the ENN basin stands out in comparison to other basins in Kenya. Another aspect which makes the ENN basin an interesting basin to focus on is the current poverty rate. The poverty rate of the ENN basin is the highest with its 66% compared to the poverty rate in other basins (Aurecon AMEI Limited, 2020b). Since flooding is accompanied by among other things economic loss, the avoidance of flooding and thus further enlargement in poverty rate is of great importance in this basin in particular. By implementing adequate flood management and by using suitable flood mitigation measures, some economic disasters can be prevented which otherwise would have further increase the poverty rate.

As a result of the above described impact of climate change and the high poverty rate in this ENN basin, this report will focus on flood risk management in this particular basin. But since this basin is still extensive, the case-study will be done in a smaller region, namely the Isiolo River Basin. This river basin includes Isiolo Town which is an urban area located at the receiving end of a watershed so the water is generated not only within its own city, but is also originating from upstream areas, resulting in an accumulation of runoff (MetaMeta, 2022). The rapid growth of population and urban area also contribute to the increased pressure on the existing drainage systems and increase in runoff (MetaMeta, 2022).

For these reasons, the Isiolo River Basin is an interesting part of Kenya to focus on by looking at the flood risk management and by advising flood mitigation measures by using several tools. But before zooming in on the Isiolo River Basin and Isiolo Town to eventually recommend certain mitigation measures, the report will first map the current flood management in Kenya. Because this is also a key issue of the water resources of the country. The organisation structure and challenges of the stakeholders of interest will be assessed.

1.2 Objectives

One of the objectives of this report is to map the current flood management in Kenya since adequate flood management becomes more important in the future as a consequence of the effects of climate change. Also, the challenges experienced in project management regarding flood risk mitigation will be mapped. The report also aims to provide a clear overview of the current geological and water resources state and other important hydrological aspects. This background information is all related to flooding, which will be discussed including elaboration of the impact of climate change on flooding and explanation of possible flood risk mitigation measures, including the SLAMDAM: a movable dam. With all this gained knowledge, the objective is to find effective flood mitigation measures for the Isiolo River Basin in particular whereof information will be provided as well before the basin will be assessed extensively. The feasibility of the SLAMDAM specifically in this river basin will be assessed by using the tools 3Di to determine the water level as a result of heavy rain events and the Flood Intelligence Service (FIS) Tool to determine the costs and benefits of the implementation. The SLAMDAM will also be compared to other possible flood risk mitigation measures. The research question which is accompanied by these objectives is defined as follows:

How does the SLAMDAM perform in flood risk reduction in comparison to other flood mitigation techniques using the FIS Tool in the Isiolo River Basin?

To provide an answer to this research question, a data analysis will be conducted, using Quantum Geograhic Information System (QGIS), 3Di, and the FIS Tool. The input data will be collected through water resources institutions in Kenya but also by using globally available data. Furthermore, a literature study will be conducted and interviews are held with several national and local organizations and communities.

1.3 Structure of the report

This report will first provide background information in the initial chapters. Chapter 2 provides general information about Kenya to sketch the context, chapter 3 discusses the geological aspects in Kenya, and chapter 4 provides information about flooding including the effect of climate change on flooding. Chapter 5 focuses on Isiolo, since the FIS Tool and 3Di will be used for the Isiolo River Basin specifically. The exact limits of the examined area will become clear in this chapter and the occurring flood types in this region and other flood-related aspects will be addressed. Chapter 6 provides information about the SLAMDAM and other possible flood risk mitigation measures which could be a possible solution to decrease the flood risk. In chapter 7, the method to fulfil the objectives will be described, including a description of the tools being used in the process and used equations later on in the report. Chapter 8, 9, 10 and 11 will provide the results: chapter 8 will provide an overview of the stakeholders, the institutional framework and the challenges they experience, chapter 9 provides more information on the findings in Isiolo River Basin and assesses the flood risks. This chapter also provides the flood maps for several extreme rainfall events. Chapter 10 provides a feasibility study of the SLAMDAM, by considering the most relevant flood maps to use in the FIS Tool to indicate the gained benefits from implementing the SLAMDAM at a particular location. Chapter 11 compares the SLAMDAM to other flood risk mitigation measures, also by implementing some measures in the FIS Tool. Finally, chapter 12 will provide the discussion and recommendations and chapter 13 will provide a conclusion of the report including the answer to the research question.

Figure 1.1: The Merire River, located upstream of Isiolo Town

Chapter 2

General information about Kenya

This chapter will sketch the context of the country of interest: Kenya. After providing some general information about the country and its history, the focus will move towards the water resources of Kenya since this is related to the objective of this report.

2.1 Geographic

Kenya is a country in North East Africa. It is surrounded by South Sudan to the north-west, Ethiopia and Somalia to the north, Uganda to the west, Tanzania to the south and the Indian Ocean coastline to the east (Google Maps, n.d.). In the south central part of Kenya lies the country's largest city Nairobi, which is also its capital. It is followed in size by Mombasa which is located on the coast. The central and western part of Kenya are characterized by the Kenyan Rift Valley (Aurecon AMEI Limited, 2020b). Isiolo, the main focus in the report later on, is in the central part of Kenya. It is located just north of Mount Kenya and it is the capital of Isiolo County.

2.2 Demo- and sociographic

Kenya has experienced an impressive growth in population since the mid-20th century due to its high birth rate and declining mortality rate. In 1963, the year Kenya got their independence, the population was estimated to be 8.5 million. In 2021, the population size of Kenya was close to 55 million inhabitants and population growth was 2,2% (The World Bank Group, n.d.). The official languages are English and Kiswahili and there are numerous indigenous languages. In the country around 85% is Christian (33% Protistan, 20% Catholic, 20% Evangelical, 7% African Instituted Churches and 4% other Christian) and around 11% is Muslim. Furthermore, Kenya has a very young population; more than 40% of Kenyan are below the age of 15 years old. In total, more than 90% of the inhabitants is younger than 55 years old and the life expectancy is 67 years. In 2021, around 28% of the population lived in urban areas and this number is still increasing over the last years. Finally, Kenya has a diverse population when it comes to ethnic groups. There is no total overview of all ethical groups, but estimates range from 50 to 120 different groups, the largest being Kikuyu (17%), Luhya (14%), Kalenjin (13%), Luo (10%) and Kamba (10%) (CIA, 2022).

2.3 Economy

Kenya is the third-largest economy in sub-Saharan Africa after Nigeria and South Africa (Standard Reporter, 2020). It can be seen as the economical, financial and transportation hub of East Africa (CIA, 2022). However, it is still defined as a lower-middle income economy. In 2021, Kenya had total Gross Domestic Product (GDP) of 110.35 billion US dollars and a GDP per capita of 2.006 US dollars. The annual GDP growth in 2021 was 7.5% but in 2015 still 29.4% of the population was living below the poverty headcount ratio at $2.15 a day (The World Bank Group, n.d.). While Kenya has a growing middle class and steady annual growth in GDP for the last decade, its economic development has been hampered by corruption and weak governance (CIA, 2022).

Accounting for 40% of the overall workforce (70% of the rural workforce) and about 25% of the annual workforce, the agricultural sector dominates Kenya's economy. The country's major agricultural exports products are tea, coffee, cut flowers, and vegetables. The high rainfall areas contribute for around 10% of Kenya's arable land and produce 70% of its national commercial agricultural output. Farmers in Arid and Semi-Arid Lands (ASAL) account respectively for the remaining 10 % and 20% (International Trade Administration, 2022). In US dollars, in 2020 the top exports of Kenya were tea ($1.2B), cut flowers ($596M), refined petroleum ($308M), gold ($262M), and coffee ($229M), exporting mostly to Uganda ($940M), Pakistan ($515M), the Netherlands ($503M), United States ($496M), and United Kingdom ($435M) (Observatory of Economic Complexity, n.d.).

2.4 History and politics

From the first century, people from the Nilotic and Bantu communities lived in Kenya. In addition, there were many Arab traders around that time. The first Europeans to come ashore were the Portuguese in 1498, led by Vasco de Gama. They then took over the important port city of Mombasa from Arab domination. It was again ceded to Islamic control in the 1600s under the Imam of Oman until it was later taken over again by Europeans: the British (Embassy of Republic of Kenya in Japan, n.d.).

In 1885, at the Berlin Conference, East Africa was divided into several territories among European powers and so in 1895 the British government founded the East African Protectorate. It was officially declared a colony in 1920 and the country was named after its highest mountain: Mount Kenya. Then in 1942, members of several tribes took an oath to fight against British colonial rule. This movement was known as the Mau Mau Movement and involved bloody fighting in which 11,000 Kenyan rebels died. In 1953, Jomo Kenyatta, later Kenya's first president, was considered to be the leader of the Mau Mau and sentenced to seven years in prison. During 1952 to 1959, Kenya was placed under a state of emergency and during this period Africans and Asians were allowed to participate in political process for the first time. Thus, the first direct elections for Africans took place in 1957. In 1962, Jomo Kenyatta was finally released. One year later, Kenya became independent and a republic with Kenyatta as its first president (Embassy of Republic of Kenya in Japan, n.d.).

In the following decades, there have been elections every 5 years, some of which have been tumultuous (NOS, 2017). In post-colonial times, British influence on the political system remained dominant. This was particularly visible in the centralised system of local government. In the early 1990s, the demand to change the political system from a single-party system to a multi-party democracy increased under pressure from the public, civil society organizations and other stakeholders who were actively lobbying and advocating for participatory and inclusive governance. Finally, in 1997 the national government agreed to consider structural changes and started a constitutional review (Nyambura & Grant, 2022).

Since its independence, Kenya has had five presidents, with William Ruto being the most recent one as he was installed on 13 September 2022 (Omulo, 2022). The new 2010 constitution replaced the 1963 independence constitution. Since then, Kenya is a presidential representative democratic republic with a multi-party system wherein the president is head of state and as well as head of government. With the adoption of the new constitution, significant changes have taken place in Kenya's governance. The people have become more central to decision-making (Gĩthĩnji, 2022). So does Article 1 of the Constitution state that '*All sovereign power belongs to the people of Kenya ad shall be exercised only in accordance with this Constitution*'. The decentralization of power also stands out. Previously, the president had a lot of power, but the new constitution more strictly separated the legislative, executive and judicial powers from each other, reducing executive dominance over the other arms of government (Nyadera, Agwanda, & Maulani, 2020).

The arms of the national government in Kenya are structured as follows(Gĩthĩnji, 2022):

- Executive: constitute of the President, the Deputy President and the rest of the Cabinet
- Legislature:
  - National Assembly (Lower house of Parliament of Kenya, in total 349 seats)
    - 290 elected from constituencies
    - 47 women elected from counties
    - 12 nominated representatives
    - A Speaker of the National Assembly, serves as an ex officio member
  - Senate (Upper house of Parliament of Kenya, in total 67 seats)
    - 47 elected by registered voters of the counties, each county constituting a single member constituency
    - 16 women nominated by political parties
    - 2 members nominated to represent the youth
    - 2 members nominated to represent people with disabilities
    - A Speaker of the Senate, serves as an ex officio member
- Judiciary: is independent of the executive and legislature and divided into Superior Courts and Subordinate Courts. The Supreme Court is the highest court in Kenya.

Finally, before the constitution of 2010, there were eight provinces in the country. This changed in the creation of 47 counties, each with its own government including two arms: legislative and executive (see Figure 2.1).

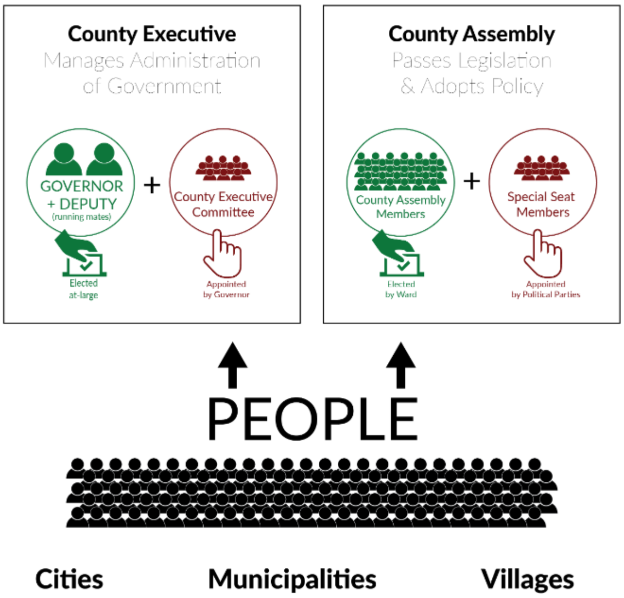


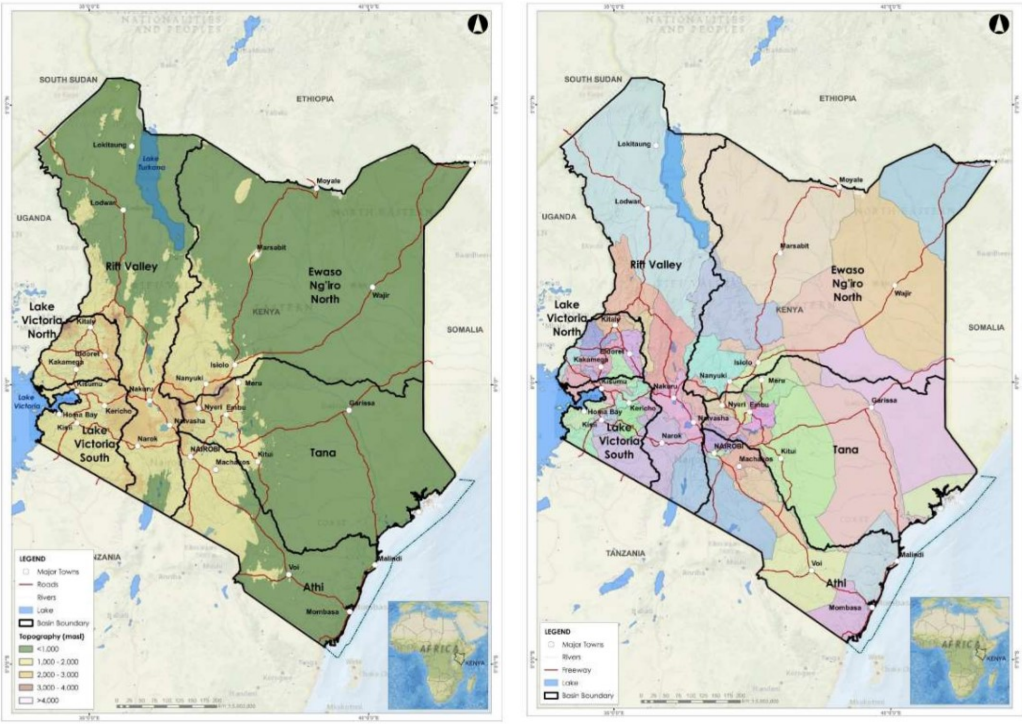
Figure 2.1: Kenya Local Government Structure
(Nyambura & Grant, 2022)

2.5 Water resources

Kenya consists of 11,230 km^2 of surface water and 571,426 km^2 of land, with the Indian Ocean as a natural border in the east. The main lakes in Kenya, contributing to a big part of the percentage of surface water, are lake Victoria and lake Turkana (Nippon Koei Co., 2013). With regard to water resources, the country is divided into six main river basins. These six main basins are (Aurecon AMEI Limited, 2020b):

1. Athi
2. Tana
3. Lake Victoria South (LVS)
4. Lake Victoria North (LVN)
5. Rift Valley (RV)
6. Ewaso Ng'iro North (ENN)

The maps in Figures 2.2a & 2.2b show Kenya, its six basins, the 47 different counties, and their borders. Some of the counties cross hydrological basin boundaries, which makes close cooperation to address water-related problems between the neighbouring counties and villages located therein essential (Aurecon AMEI Limited, 2020a).



(a) Overview map showing the six basins of Kenya

(b) Kenya counties in relation to the main six basins

Figure 2.2: Overview of six basins and counties (Aurecon AMEI Limited, 2020b)

Following chapters will provide more information about the ENN basin specifically since this is the focus area of this report. This will include more information about the Isiolo county and its river basin as this is the area for which the feasibility of the SLAMDAM by using the FIS Tool is ultimately carried out.

2.6 Problem analysis

At the moment, the water resources of Kenya are threatened by multiple issues. As listed by the Water Resources Authority (WRA) these included (Aurecon AMEI Limited, 2020b):

- Human conflict
- Water quality
- Soil erosion and sedimentation
- Climate change
- Catchment degradation
- Inadequate monitoring
- Planning and management
- Water availability and supply issues
- Inadequate resources
- Uneven spatial and temporal distribution of water resources
- Anthropogenic encroachment on environmentally sensitive areas
- Inadequate flood and drought management

As each catchment has its own unique characteristics, each catchment has its own location-specific challenges and issues. For effective and efficient water resources management and planning, it is necessary to include these identified characteristics and issues. Therefore, following chapters elaborate on the characteristics of the ENN basin and Isiolo specifically. To ensure a systematic approach towards the integration of the identified issues for the basin planning process, the WRA has designed a framework which gives a good overview of the key issues.

The specific water resources-related issues described in the figure below for the whole of Kenya correspond to the key issues that were classified in the ENN basin (Aurecon AMEI Limited, 2020a). The key issues are categorised into biophysical, socio-economic, water resources and institutional issues.

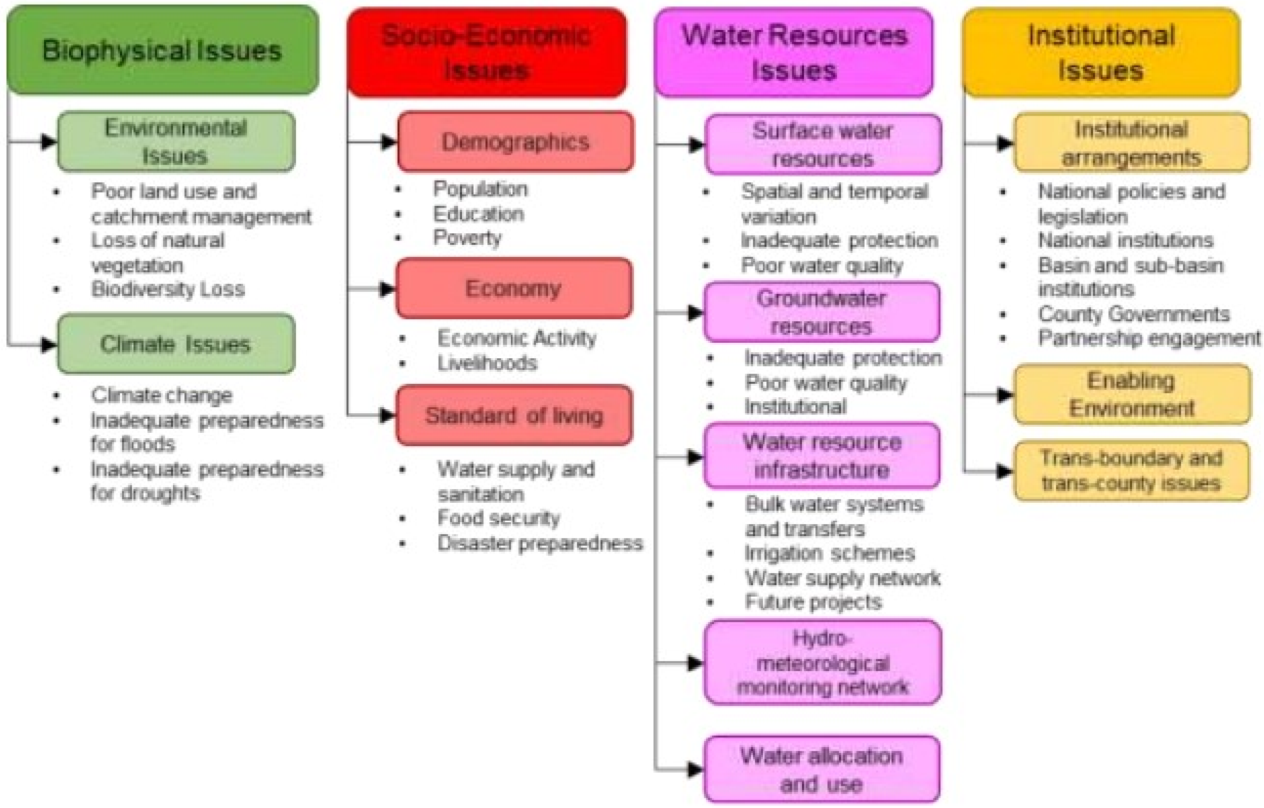


Figure 2.3: Key issues in Kenya, (Aurecon AMEI Limited, 2020b)

Besides water resources issues on itself, this issue is also related to many other issues whereof one of them is poverty. Poverty remains a big issue as indicated within the socio-economic issues and inadequate flood risk management can contribute to even more poverty. The average poverty rate of the six basins is currently as follows:

Table 2.1: Average poverty rates per basin (Aurecon AMEI Limited, 2020b)

Basin	Poverty rate
Athi	38%
Tana	40%
LVS	46%
LVN	38%
ENN	66%
RV	52%

As can be seen from the Table 2.1 above, the poverty rate in the ENN basin is the highest and the poverty rate in the LVN basin is the lowest.

2.7 Stakeholders and legal system

The water resources in Kenya are managed by several organisations and institutions. Moreover, there are a lot of important laws, policies, and plans that influence the implementation of new technologies like SLAMDAM. The involved stakeholders, institutional framework and important laws, policies, and plans will be shown and described in chapter 8. Chapter 8 also explains which stakeholders were interviewed during this project. In addition, stakeholders were contacted during webinars, site investigations, and demonstrations. An overview of these stakeholders is given in section 8.3. From all interactions with stakeholders, an overview of the challenges around project implementation is made based on their experiences. The focus of these challenges is on flood risk mitigation, but people were free to give their own input on other types of projects as well.

For now, it is important to be aware of the following water-resources related stakeholders that are relevant for this report:

- Ministry of Water, Irrigation and Sanitation
- Ministry of Agriculture, Livestock, Fisheries and Co-operatives
- Ministry of Devolution and ASALs
- Ministry of Environment and Forestry
- Water Resources Authority (WRA)
  - National office
  - Sub-regional offices
- Kenya Meteorological Department (KMD)
- Basin Water Resources Committee (BWRC)
- Water Resources User Association Isiolo (WRUA Isiolo)
- National Drougt Management Authority
  - National office
  - Sub-regional office
- National Environment Management Authority (NEMA)
- Isiolo County (including relevant ministeries and departments)
- Kenya Red Cross
- Netherlands Development Organization (SNV)
- National Disaster Operation Centre (NDOC)
- National Disaster Management Unit (NDMU)
- Embassy of the Kingdom of the Netherlands
- Centre for Training and Integrated Research in ASAL Development (CETRAD)
- The Trans-African Hydro-Meteorological Observatory (TAHMO)

Chapter 3

Geology of Kenya

As listed before, the water resources of Kenya are threatened by multiple issues of which also ground related issues, such as soil erosion and sedimentation. Also the water resources issues as pointed out in Figure 2.3 are related to these issues. Therefore, a good understanding of the geology of Kenya is of importance. In this chapter more detailed information on the geological history and different land forms in Kenya is given. Furthermore, it is explained how soils have formed and what factors influence soil-formation.

3.1 Geological history

Kenya is known for its complex geological history. Soils can range from clayey and volcanic soils in mountainous regions to sandy soils in floodplains. In the history of Kenya five geological successions can be distinguished (Akech, Omuombo, & Masibo, 2013):

1. The Archaen (Nyanzian & Kavirondian)
2. Proterozoic (Mozambique Belt & Bukoban)
3. Palaezoic/Mesozoic sediments
4. Tertiary/Quaternary volcanics and sediments
5. Pleistocene to recent soils

Recent soils consist of alluvial beach sands, evaporites, fossil coral reefs and sandstones at the east coast of Kenya, starting in age from the Jurassic. The Rift Valley, which runs through Kenya from north to south, is part of an intra-continental ridge. Here, alluvial and lacustrine sediments can be found as well as Tertiary volcanic rocks from the younger volcanoes. Adjoining to Lake Victoria in the west, are the Archaen Nyanzian meta-volcanics and Kavirondian meta-sediments (Akech et al., 2013). An overview of the general geology can be found in the figure below:

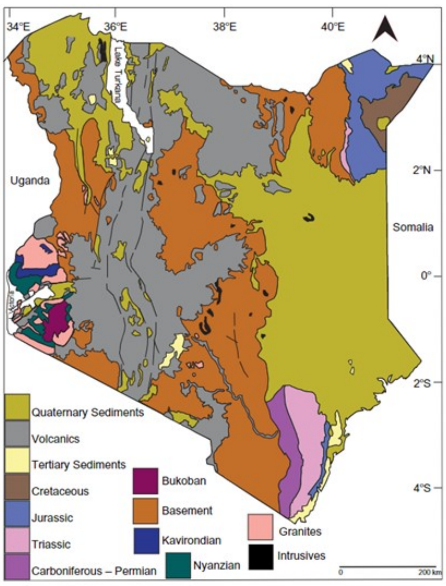


Figure 3.1: The general geology of Kenya (Akech et al., 2013)

3.2 Physical regions/landforms

The topography of Kenya stretches from sea level at the east coast to about 5,200 m above sea level (a.s.l.) at the peak of Mt. Kenya. The land is characterised by plain landforms with gently sloping areas. The higher slopes are limited to mountainous areas (Aurecon AMEI Limited, 2020b). Based on the relief intensity, which is the vertical difference between higher and lower parts of the landscape and the slope class, the following landforms can be recognised in Kenya (Akech et al., 2013):

- Mountains and major scarps
- Volcanic foot ridges
- Foot slopes and pediments
- Piedmont plains
- Plateaus and high-level structural plains
- Upland and dissected peneplains
- Plains
- Floodplains
- Lowlands

The explanation and map of the different landforms can be found in Appendix A and B.

3.3 Soils in Kenya

Most soils in tropical Africa are deeply weathered. This indicates that these soils are very old. Low levels of essential nutrients, such as phosphorus, potassium, calcium and magnesium, are measured as they have been leached out over time. Natural ecosystems have evolved to survive in such poor soil conditions by managing a fragile nutrient cycle (European Commission, 2013). Small modifications, for example, through intervention by humans, can imbalance this cycle. In this section, an elaboration of the different soil-forming factors and their association with Kenya will be given.

3.3.1 Soil-forming factors

Characteristics of soils vary considerably from place to place. Many factors such as climate, topography, as well as geological factors play a big role. According to soil scientist Hans Jenny (1941), the variables that influence the characteristics of a soil can be described with the following formula:

$$soil = f(p, t, c, o, t) \tag{3.1}$$

In this formula the soil is dependent to the following variables (European Commission, 2013):

1. Parent material
2. Topography or position in the landscape
3. Climate
4. Organisms, especially vegetation
5. Time

Beside these factors, an important addition is human activity. Soil processes and characteristics can be significantly influenced by human land use. Think about drainage, deforestation or the addition of fertilisers. These variables that influence the soil will now be elaborated.

1. Parent material

The parent material refers to the material (rock) from which the soil has been derived; its geological origin. There are three types of rocks: igneous, sedimentary, and metamorphic rocks.

Igneous rocks are formed when molted magma, generated by local heating and melting of rocks within the Earth's crust, cools down. It solidifies by crystallizing into a mosaic of minerals to form an igneous rock (Waltham, 2009).

Sedimentary rocks are formed by deposition of weathered material. Natural transport processes deposit the sediment load. Burial of these sediments by more layers deposited on top eventually turn it into a sedimentary rock (Waltham, 2009).

Metamorphic rock are created by changes intense heat and/or high pressures. This takes place in the solid state of igneous or sedimentary rocks (Waltham, 2009).

The nature of the parent material can have a large contribution to the soil characteristics. For example, lime-rich soils, which are generally derived from calcareous rocks, can offset the development of acidic conditions in the ground. Or the texture of soils, which is largely determined by the parent material, influences the porosity and thus the drainage of soils.

The rock of Africa is in general very old and in most cases it is crystalline and derived from igneous sources. Often it has been altered chemically (metamorphised) (European Commission, 2013). Because the continent is slowly being torn in two parts along the Great African Rift Valley, volcanic activity is very common. As this Rift Valley crosses Kenya from the north to the south in the west of the country, extrusive volcanic rocks and methamorphic igneous rocks can be found here. In the east of Kenya alluvium and colluvium soils can be found. Figure 3.2 shows tephra deposits in volcanic ranges. The profile shows that the soil is built up from several volcanic eruptions, which are recognisable from the different colours of the various volcanic ash layers.

Figure 3.2: Photo showing young tephra deposits in volcanic ranges in Kenya (European Commission, 2013)

2. Topography

The relief or topography of a land has a big influence on the formation of soils. This is due to its influence on local climate, vegetation and movement of water (European Commission, 2013). Mountains, for example, affect the amount and intensity of precipitation and a local slope controls the drainage and movement of material.

The position of soils in the topography is also important. Soils at the top of a slope tend to be freely draining while those at the foot are generally poorly drained. Different soils may form while the parent material, climate and even vegetation are the same. Figure 3.3 illustrates the influence of topography on the soil profile. A description and map of the different landforms in Kenya can be found in Appendix A and B.

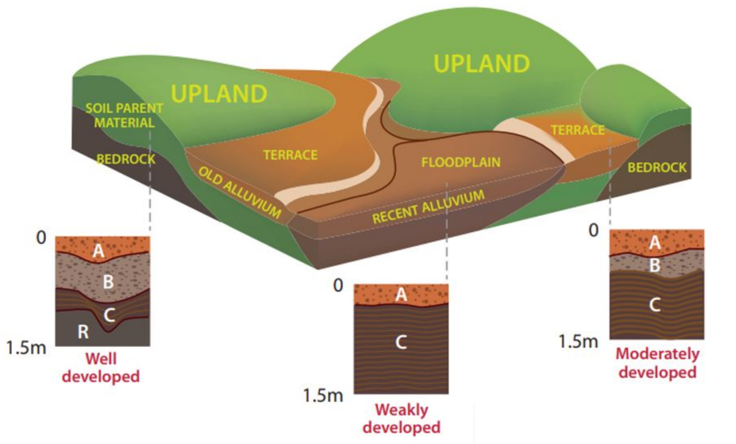


Figure 3.3: The influence of topography on soil formation (European Commission, 2013)

3. Climate

Climate describes the weather conditions prevailing in an area over a long period of time. This means that climate can be associated with the temperature and moisture levels in an area. As these levels affect weathering processes and biological activity, soil formation depends enormously on the occurring climate. In areas associated with high temperature and humidity, chemical weathering will be very prominent, whereas physical weathering will dominate in hot, dry desert regions (European Commission, 2013).

With the equator running through the centre of Kenya, rainfall is well distributed throughout the year and temperatures are relatively constant (European Commission, 2013). Temperatures vary between the 18°C and 33°C, with an average temperature of 25°C (Figure 3.4). Although these temperatures can vary greatly throughout the country, with the highlands experiencing cooler temperatures than coastal regions and lowlands. The main capital Nairobi, in the southern inland highlands, experiences an annual mean temperature of 18°C. Near Lake Victoria, at the border with Tanzania at 1350 m altitude, an annual mean temperature of 26°C is measured. The coastal lowlands experience a constant high temperature and humidity which is associated with equatorial climates. The Northern part of Kenya is more dry and hot throughout the year (Met Office, 2011). The average annual precipitation is around 680 mm, but this can vary from 250 mm in the northern areas to about 2,000 mm in the western regions (The World Bank Group, 2021).

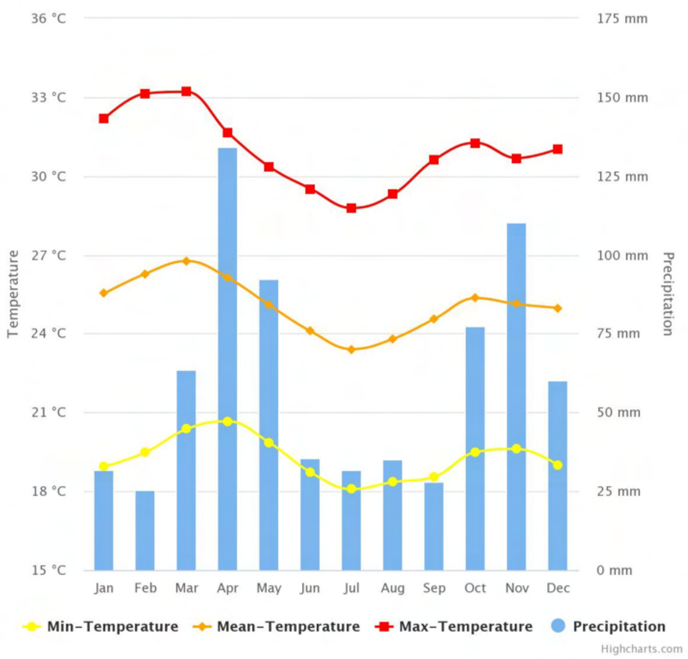


Figure 3.4: Monthly climatology of min-, mean- and max-temperature & precipitation from 1991 - 2020, Kenya (The World Bank Group, 2021)

Humid conditions lead to more chemical weathering and higher levels of organic matter. But it also leads to leaching of minerals and organic matter. Long periods of rain can lead to soil erosion and saturated soils. With the changing climate, higher temperatures are expected in the future, which have its effect on weathering and thus soil forming processes. A more detailed elaboration on the impact of climate change on rainfall in Kenya and flooding in particular is given in section 4.3.

Appendix C shows the land cover in Kenya. Kenya consists mainly of arid and semi-arid lands (ASAL) alternated by the highlands around Mount Kenya. In the highlands the rainfall is well distributed throughout the year and temperatures are constant (European Commission, 2013). In the arid and semi arid zones, the average rainfall is less than 600 mm which falls only in the rain seasons.

4. Organisms

Soil formation is affected by all living organisms (plants and animals). Organic matter is added to the soil by organisms through decomposition and breakdown. The biological activity in the soil is dependent on climate, topography and soil characteristics such as depth and chemistry (e.g. pH, salinity).

5. Time

Physical, chemical and biological processes are the drivers of soil formation. These processes, however, rarely remain constant over time. Over geological timescales, new sources of parent material can be introduced. With changing global climates on shorter timescales (100-1000 years), different soils will be formed. The different geological successions were already described in the beginning of this chapter in section 3.1.

6. Human activity

As human life depend on water and food, human settlement used to be dependent on climate, availability of water and the presence of fertile soils. Urban patterns which are visible today match these conditions (European Commission, 2013). However, humans can have a negative impact on soil formation through land management practices which disturb the natural processes and change the chemical and physical characteristics of the soil. An example of this is deforestation. From 2001 to 2021, 9.8 % of tree cover loss in Kenya resulted from deforestation (World Resources Institute, n.d.). This increases the risk of soil erosion and sediment flow.

3.3.2 Threats to soils

Besides deforestation there are other threats to soils caused by human activity. If these soil problems are not countered, soil will eventually lose its function. This is known as soil degradation. Key issues in Kenya regarding soils are recurring droughts, floods during rainy seasons, pollution from wastes, increased use of pesticides and fertilisation, soil erosion and desertification (European Commission, 2013).

Also the climate change can have a great effect on soils, as climate is one of the major soil forming factors. Temperature, rainfall and changes in atmospheric conditions affect the soil ecology and organic matter levels in the soil. This determines soil characteristics such as structure, water regimes, pH, and nutrient levels. Besides this, the expected higher temperatures also influence the rate of breakdown of organic matter in the soil. This accelerates the release of carbon dioxide and methane into the atmosphere even more due to an increased respiration (European Commission, 2013). Additionally, changes in precipitation and more extreme hydrological cycles will also alter soils. It means that soils will experience either intense rain storms or prolonged periods of droughts. This can lead to increased vunerability to soil erosion and this can on its turn result in loss of topsoil nutrients and stored carbon. Rainfall patterns also have an effect on soil structure and acidity levels. Together, it determines the capability of soils to store water.

Chapter 4

Flooding in Kenya

The previous chapters have sketched the situation in Kenya and provided background information about the geological aspects in Kenya. They are respectively related to flood risk management and flooding (e.g. erosion or sedimentation). This chapter will provide more relevant information about flooding in Kenya, including information about the effect of climate change on the frequency and magnitude of flooding.

4.1 Flood-prone regions in Kenya

The National Water Master Plan of Kenya has pointed out 21 areas subject to the flood disaster management plan. Prior to this management plan, an adequate flood disaster management system was lacking because the frequency of flooding was low. Since the 1997-1998 El Nino floods flooding occurred more and its frequency is expected to increase in the upcoming years due to the effect of climate change. This increases the importance of adequate flood risk management (Nippon Koei Co., 2013). Section 4.3 will elaborate on the effects of climate change on flooding. The 21 defined areas by the national water master plan are given in Table 4.1:

Table 4.1: Proposed Areas Subject to Flood Disaster Management Plan (Nippon Koei Co., 2013)

Catchment Area	Proposed Examination Area
LVN	1. Yala Swamp
LVS	2. Kano Plain, 3. Sondu River mouth, 4. Kuja River mouth, 5. Kisumu
RV	6. Middle/Lower Turkwel, 7. Lower Kerio, 8. Nakuru, 9. Narok, 10. Mogotio
Athi	11. Downmost Athi, 12. Lumi River mouth, 13. Nairobi City, 14. Kwale, 15. Mombasa
Tana	16. Lower Tana, 17. Ijara
ENN	18. Middle/Lower Ewaso Ng'iro North, 19. Wajir, 20. Mandera, 21. Isiolo

4.2 Types of floods in Kenya

During the wet season from March until May (long rains) and October until December (short rains) the most seasonal floods occur in the largest part of Kenya (the western, northern, eastern, central and southeastern parts of the country). The excessive flooding is linked to El Niño and La Niña episodes that can lead to extreme weather. The major floods occur mostly in the coastal region of Kenya, the Winam Gulf of Lake Victoria, and in the Lower Tana basin (Government of Kenya, 2016).

Overall, the most occurring floods in Kenya are riverine floods, but ASALs, covering over 80% of the country, are particularly vulnerable to flash flooding (Government of Kenya, 2016). Flash floods are suddenly occurring floods as a result of heavy rainfall events and these floods are common in areas with steep slopes, narrow valleys, and dry land. In areas with slopes heavy rainfall can cause fast flowing water because the water gathers on the slopes and this is rapidly directed downstream to a flat area. In dry areas with barely vegetation rain results in overland flow rather than infiltration into the ground, also resulting in flash floods in case of heavy rainfall (Camp, 2022).
Urban areas in specific can also be effected by urban flooding. Rapid urbanisation and poor urban planning has caused less green areas where infiltration can take place and therefore urban flooding happens more frequently (Government of Kenya, 2016).

Both pluvial flooding and fluvial flooding can occur in Kenya, and they can also possibly occur as a result of the same rainfall event (Met Office, 2011).

Pluvial flooding is the direct result of heavy rainfall. This heavy rainfall results in overland flow if it is not able to infiltrate into the ground, for example after a long period of drought, or if it exceeds the capacity of artificial drainage systems. Triggers for pluvial flooding are high intensity, short-duration rainfall events, but also low intensity events with a longer duration can cause pluvial flooding. Melting of snow can also be a cause, so the cause does not necessarily needs to be close to the river channel. Extreme rainfall events are a good indicator for pluvial flooding. Nevertheless, extreme events do not by definition have to result in pluvial flooding, since it is also dependent on many other factors like soil type, antecedent soil moisture, land cover (urbanisation), sub-daily distribution of the rainfall, and the state of the artificial drainage systems (Met Office, 2011).

Fluvial flooding is linked to the flow in the rivers. This river flow can exceed the capacity of the river channel or the river banks can break. The floodplain can get flooded as a result. The influencing rainfall-runoff process is dependent of several factors: soil type, antecedent soil moisture, infiltration, land cover, evaporation, topography, the memory of the system (stored groundwater), and the partitioning of precipitation into rainfall and snowfall. Other complications are among other things the presence of artificial river embankments and other man-made structures, since it affects whether a river flow exceeds the river channel capacity and where the excess flow will flow to (Met Office, 2011).

4.3 Effects of climate change on flooding

Kenya's National Climate Change Action Plan 2018-2022 has set several priorities with regard to climate change actions to take. One of these top priorities is disaster risk management, so to reduce risks to communities and infrastructures resulting from climate-related disasters. Drought and floods are climate-related disasters and for flood the aim is to improve the ability of people to cope with floods and increase the resilience of infrastructure. Another aspect is to improve coordination and delivery of disaster risk management activities to deal with floods effectively (Government of the Republic of Kenya, 2018). This action plan is made to cope with the climate change. The effects of climate change on flooding is discussed in this section.

Climate change affects Kenya in several ways. The trend of rising temperatures since 1960 is expected to continue. With regard to rainfall, the patterns have changed and became more unpredictable and the average rainfall will possibly increase, especially from October to December. Also, the proportion of rainfall that occurs from heavy events is expected to increase (Government of Kenya, 2016). Overall, extreme weather events like floods will increase in frequency and intensity as a result of climate change. This affects the rainfall and the risk of flooding.

The Met Office has used several scientific models to predict the effect of climate change country specific. The CMIP3 model ensemble shows precipitation in East Africa will increase over 20% in Kenya. The figure below shows this prediction (Met Office, 2011):

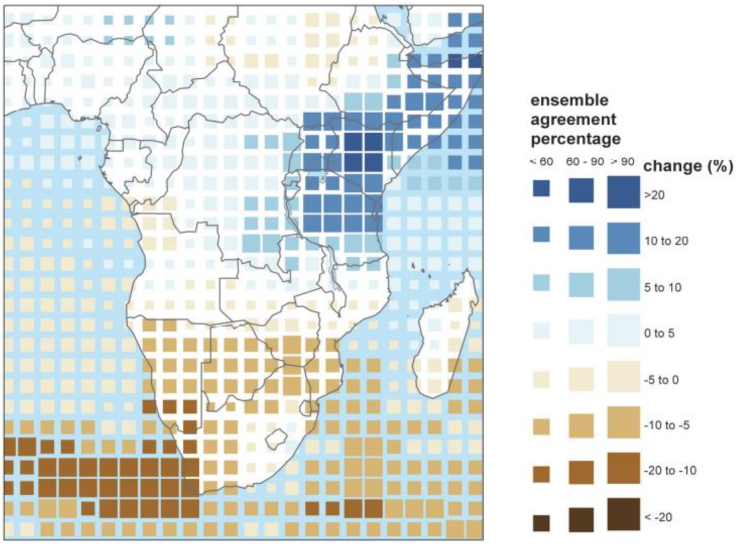


Figure 4.1: Percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the sign of the change (Met Office, 2011).

The size of the grid shows the amount of agreement of the models. As can be observed from the figure, the average annual precipitation is expected to increase by 2100, with a high level of agreement between the models on the sign of change. In comparison to the rest of the continent Africa, East Africa stands out with regard to the expected increase in rainfall.

Models on both global- and catchment-scale assessments show consistently that the flood magnitude could increase with climate change. These predictions are supported by simulations (Met Office, 2011).

The best prediction for change in pluvial flooding are changes in extreme rainfall events. One global modelling study suggests that in the period 2001-2030 the return period of what used to be a 100-year flood event will reduce to a return period of less than 60 years in some (mostly southern) parts of Kenya. In the period 2071-2100 this return period will even be lowered to less than 30 years in most parts of Kenya. This suggests that the probability of extreme flooding events could get more than tripled (Met Office, 2011). This lower return period means a higher frequency of flooding. The frequency of floods caused by rainfall events has already shown to increase in East Africa. The average used to be less than three events per year in the 1980s, and from 2000 to 2006 the average has increased to 10 events per year (Government of the Republic of Kenya, 2018). As stated in section 4.2, some areas are very vulnerable to flash floods as a result of extreme rainfall events. The magnitude of flash floods is expected to increase in the future (Aurecon AMEI Limited, 2020a). Another effect on rainfall and thus pluvial flooding are changes in the El Niño-Southern Oscillation which could change significantly due to climate change. However, none of the global climate models have yet analyzed rapid changes in behaviour, although change cannot be ruled out due to uncertainty and biases in the models (Met Office, 2011).

The effect of climate change on fluvial flooding is estimated by using an indicator for percentage change in average annual flood risk within Kenya. It uses a flood frequency curve, a generic flood magnitude-damage curve, and grid cell population which gets summed across a region. It produces a population-weighted average annual damage. This model shows a balance more towards higher flood risk: three quarters of the models project an increase. The mean of the projections is an increase in average annual flood risk of approximately 50%. By 2100, the balance shifts even more to an increased flood risk (Met Office, 2011). And with regard to the seasonality of flood events, there is some tendency for peak flows to occur one month later than currently in some parts of Kenya (Met Office, 2011).

Climate change also results in sea level rise. Kenya is surrounded by the Indian Ocean on the east side of the country and five counties are connected to the coastline. Expansion of the ocean due to warming of the ocean and melting of land-based ice because of climate change results in sea level rise on the coastline on Kenya which is expected to be greater than the global average (Government of the Republic of Kenya, 2018). This sea level rise forms a risk for the coastal counties and their population and in combination with extreme weather events it is likely to intensify flooding because most of the land near the coastline is low-lying (Government of Kenya, 2016). Therefore, Kenya is considered to be highly vulnerable to sea level rise and impacts could be severe, especially in the Mombasa district (Met Office, 2011).

As discussed in section 2.5, Kenya is divided into six basins. These basins have been assessed in the National Integrated Water Resources Management and Development Plan prepared for the WRA. The climate change impact on all six basins was considered. The following Tables (4.2 & 4.3) show the percentage change of mean annual precipitation (MAP) of the basins for the period 2018-2050:

Table 4.2: Projected changes in maximum and minimum temperatures and MAP per basin (RCP4.5; 2050) (Aurecon AMEI Limited, 2020b)

	Athi	**Tana**	**LVS**	**LVN**	**RV**	**ENN**
Change max temp (°C)	+1.18	+1.22	+1.25	+1.22	+1.24	+1.03
Change min temp (°C)	+1.31	+1.33	+1.35	+1.44	+1.46	+1.22
MAP (2018) (mm)	749	673	1316	1536	510	377
MAP (2050) (mm)	786	723	1349	1606	562	418
% change MAP	+4.9%	+7.4%	+2.5%	+4.6%	+10.2%	+10.9%

The surface water change and groundwater potential change was also considered for each basin, as shown in table 4.3:

Table 4.3: Climate change impacts (RCP 4.5; 2050) on surface water and groundwater availability (Aurecon AMEI Limited, 2020b)

Basin	**Surface water (MCM/a)**			**Groundwater (MCM/a)**		
	2018	**2050**	**% change**	**2018**	**2050**	**% change**
Athi	2 555	2 657	+4.0%	549	562	+2.4%
Tana	7 082	7 365	+4.0%	693	745	+7.5%
LVS	6 770	6 674	-1.4%	292	303	+3.8%
LVN	5 622	5 177	-9.2%	216	217	+0.5%
RV	2 682	2 604	-2.9%	398	411	+3.3%
ENN	2 180	2 376	+9.0%	449	501	+11.6%
TOTAL	**26 891**	**26 853**	**-0.14%**	**2 597**	**2 739**	**+5.5%**

As Table 4.2 and 4.3 show, the percentage change of MAP, surface water, and groundwater potential is the highest for the ENN basin. The unit MCM/a stands for Million Cubic Meters per acre.

4.4 Consequences of floods

Extreme weather events like floods can cause widespread damage. 60 % Of disaster victims in Kenya are the result of flood-related fatalities. For example, flooding in 2018 resulted in 183 loss of lives, displacement of more than 225,000 people, and closing of more than 700 schools (Government of the Republic of Kenya, 2018). Several effects of flooding will be described in this section.

To begin with, floods can lead to loss of live or displacement of people across counties. Apart from harming human life, it can also sweep away livestock like sheep and goats. Besides damaging livestock, floods can also harm agriculture by damaging cropland or by causing soil erosion on pasturelands or the agriculturally productive river valleys. This soil erosion undermines the sustainability of crop and livestock production on the effected land (Atkins, 2020). Irrigation infrastructure such as pumps and pipes can also be directly damaged, possibly resulting in food insecurity or an increase of food prices, in some cases by over 200% (Government of Kenya, 2018) (Met Office, 2011). This loss contributes to poverty in the affected region.

(a) Seasonal flooding in Mandera County impacting crop production (Mandera County Government)

(b) Flooding from the Yala River in the LVN Basin

Figure 4.2: Consequences of floods (Aurecon AMEI Limited, 2020b)

Also the infrastructure gets harmed by floods. Damage to infrastructure like roads, water pipelines, bridges, and power lines causes a loss to the national economy. For example, the damage to the infrastructure caused by the 1997/1998 El Niño rains was approximated to be one billion US Dollars (Government of Kenya, 2016). Access to for example health facilities can be disabled by destruction of infrastructures directing to these facilities. Floods can also directly disable access to health and other facilities. It can lead to destruction of all kinds of properties like schools, markets, and health facilities (Government of Kenya, 2018).

Flood events can also influence health in another way. It often enhances the formation of waterborne or sanitation-related diseases, such as cholera, malaria, and diarrhoeal diseases (Government of Kenya, 2016).

These environmental diseases normally associated with contaminated water and poor sanitation can reach epidemic levels in areas where water and sanitation facilities are inadequate or are in poor state, especially with floods related to El Niño events (Government of Kenya, 2010).

The environment can also be harmed via floods. Floods can carry fertiliser and pesticide residues into water bodies. This can lead to eutrophication, which is harmful for water quality and aquatic life (Government of Kenya, 2010). Besides, floods can affect the hydroelectric power generation because of siltation of dams due to floods. This siltation, mainly caused by heavy floods, reduces the gross storage capacity of a dam resulting in a decline in hydroelectric power production (Government of Kenya, 2010).

Due to among other things the effects described above, the economic loss of floods in Kenya is estimated to be around 5.5 % of GDP every seven years (Government of the Republic of Kenya, 2018).

Chapter 5

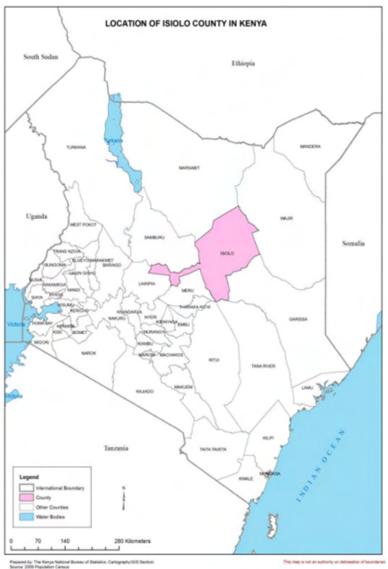
Isiolo

For this project, the Isiolo River Basin is examined. This basin is located entirely in one of the six main basins, namely the ENN basin (see Figure 5.4). As described in section 4.3, the ENN basin is most subject to the effects of climate change when considering the percentage increase in rainfall, surface water, and groundwater potential, and therefore it is an interesting basin to focus on. Besides, the poverty rate in this basin is the highest as can be seen in Table 2.1, and since floods are accompanied by among other things economic loss, it is of great importance to further avoid economic loss for this basin. These aspects contribute to the fact that this area should be protected by river structural measures according to the National Water Master Plan 2030, which defines 21 flood prone areas as already shown in Table 4.1 whereof one of them is Isiolo (21). A general introduction to flood risk and its hazard are addressed in this chapter, section 5.6. The more specific flood risk assessment for the Isiolo River Basin is carried out in chapter 9. Furthermore, this chapter provides information about Isiolo and its hydrological, geological, and water and flood related aspects. The more recent findings about, for example, recent floods are addressed in chapter 9 as well.

5.1 General information about Isiolo

Figure 5.1a shows the geographical location of the ENN basin in Kenya. The total area that is covered by the ENN Basin is 209.918 km^2, which is approximately 36% of the total area of Kenya. Overall, the ENN basin has a low population density although it is the largest river basin of the six basins in Kenya. This is due to the fact that the basin falls mostly in Arid and Semi-Arid land. However, the basin does have some urban area whereof one of them is Isiolo Town, the capital of the similarly named county (Aurecon AMEI Limited, 2020a). It is a strategically located city in central Kenya and has great economic importance for the region (Atkins, 2020).

(a) ENN Basin location in Kenya (Aurecon AMEI Limited, 2020a)



(b) Isiolo County location in Kenya (County Government of Isiolo, 2018)

Figure 5.1: Location ENN basin and Isiolo County within Kenya

As mentioned in 2.4, under the new Constitution of 2010 Kenya has been divided into 47 counties. In Figure 5.1a the location of Isiolo and its neighbouring counties in Kenya are shown. As can be seen in Figure 5.1b, Isiolo county is located in the Upper Eastern Region of Kenya. The county covers approximately 25.700 km^2 and its capital Isiolo Town lies 285 km from Nairobi (County Government of Isiolo, n.d.).

Of the ten counties that fall within the ENN basin, only eight of them are fully enclosed within the basin borders, see Figure 5.2. This means that some counties cross hydrological boundaries and therefore have to engage with multiple WRA offices. The counties within the ENN basin include Garissa, Isiolo, Laikipia, Mandera, Marsabit, Meru, Nyandarua, Nyeri, Samburu, and Wajir (Aurecon AMEI Limited, 2020a).

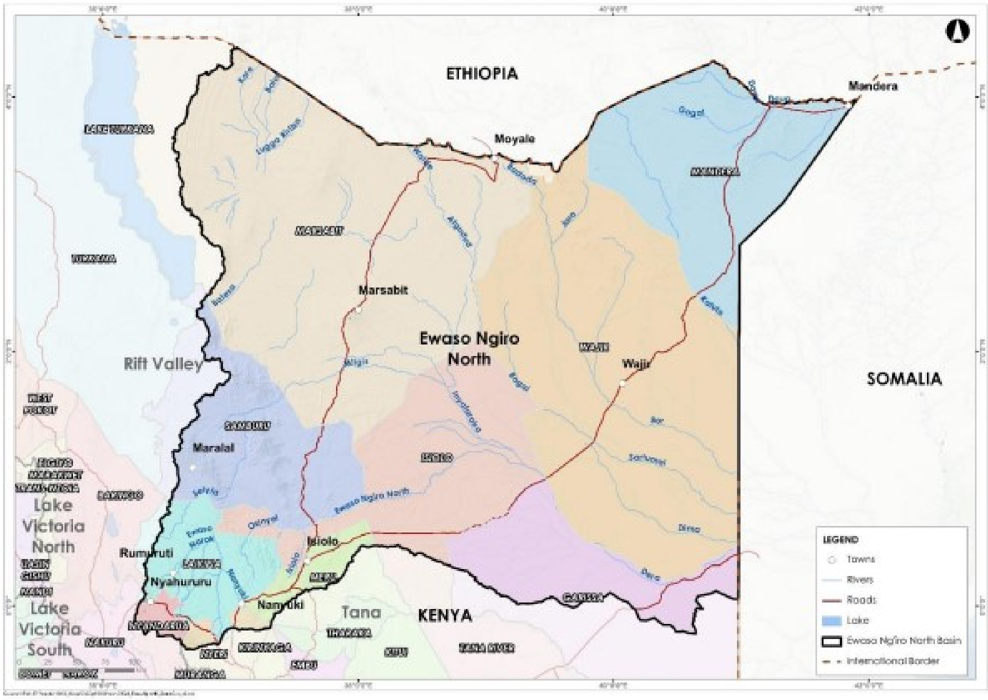


Figure 5.2: Counties within ENN Basin
(Aurecon AMEI Limited, 2020a)

Demographic
About half of the population from Isiolo County lives in Isiolo Town: in 2018, 80,500 people lived in Isiolo Town and the County had a population of 159,000. Although the county's overall population is growing at a slower rate, Isiolo Town has a growth rate higher than the growth rate of the whole of Kenya (Atkins, 2020). This is as a result of the national projects such as the LAPSSET, the Resort City, and making Isiolo Airport into an International Airport which is expected to attract many people to live in Isiolo Town (County Government of Isiolo, 2018). The total population of Isiolo County is therefore expected to be about 280.000 by 2030 (County Government of Isiolo, 2018). The population in Isiolo Town itself is expected to increase to 159,770 by 2030 (MetaMeta, 2022). In the County, there is tribal diversity including Borana, Meru, Somali, Turkana and Samburu. As in all of Kenya, the population is very young. About 44% are under 15 years old and 51% are between 15-64 years old (County Government of Isiolo, 2018). Finally, 65% of the county population lives below the poverty line, ranking it 39th out of 47 counties. The county holds the same place when it comes to inequality ranking (Atkins, 2020). With regard to education, Isiolo Town has a high percentage (46%) for secondary-education people compared to other national urban areas (37%) (Atkins, 2020).

Economic situation
Isiolo has a strategic location in central Kenya. It is located on the Lamu Port, South Sudan Ethiopia Transport (LAPSSET) transit corridor (County Government of Isiolo, n.d.). This is an ambitious infrastructure project for highways, rail and oil pipeline connections between Lamu (Kenya), Addis Adeba (Ethiopia) and Juba (South Sudan) with Isiolo as the connecting factor. The plan further includes turning Lamu, Isiolo and Lake Turkana into Resort Cities to boost tourism and develop three international airports here (LCDA, 2022)(County Government of Isiolo, 2018).

Furthermore, Isiolo County is part of the regional economic bloc Frontier Counties Development Council (FCDC). These are 10 northern counties that have been marginalised for many years. The FCDC covers 61%

of Kenya's land area while contributing only 5% to national output with agriculture including livestock being responsible for half of the bloc's output (Atkins, 2020). Isiolo County is the smallest economy in Kenya with respect to Gross County Product (GCP) at KSh 15.85 billion, whereas the national average is KSh 160.1 billion. Given the small population size of Isiolo County, the county still ranks 33th out of 47th when it comes to GCP per capita. Although the GCP growth of 4,9% between 2013-2017 is higher than the average of the FDCD region (4,3%), the growth rate is lower than the national rate (5,6%) (Atkins, 2020). The main economic activities include pastoralism and cattle trading, agriculture, and tourism. The main sources of income for the local economy is livestock (70%), small scale businesses (20%), and tourism and wildlife (10%) (County Government of Isiolo, n.d.). However, the main sectors that contribute to the GCP from large to small are public services (29%), agriculture, forestry and fishing (21%), retail, hospitality and other services (17%), and construction and logistics (17%) (Atkins, 2020).

Administrative

Isiolo County is subdivided into two constituencies, three sub-counties and 10 wards (County Government of Isiolo, n.d.). Figure 5.3 gives an overview of the different wards in Isiolo County. Table 5.1 shows the population of the Isiolo sub-counties in 2019 and its sizes.

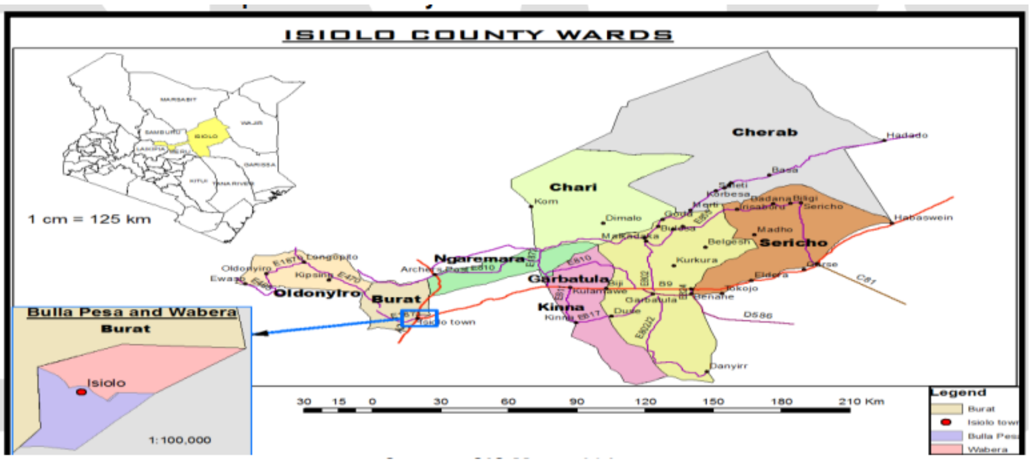


Figure 5.3: Isiolo County Administrative and Political Units
(County Government of Isiolo, 2018)

Table 5.1: Isiolo Sub-Counties & Wards (Kenya National Bureau of Statistics, 2019) (County Government of Isiolo, 2018)

Constinuency	Sub-County	Area (in sq. km)	Population (in 2019)	Wards
Isiolo North	Isiolo	3.269	121.066	Walbera
				Bulla Pesa
				Burat
				Ngaremara
				Oldonyiro
	Merti	112.612	147.206	Chari
				Cherab
Isiolo South	Garbatulla	9.819	99.730	Kinna
				Garbatulla
				Sericho
Total		25.700	268.002	10

As mentioned in section 2.4, each county in Kenya has it own government that exist of two arms: legislative and executive. The executives exists out of a governor, the governor deputy and the county secretary (BRON website Isiolo). The Isiolo County has seven ministries and eighteen different departments. For this project the Ministry of Water Sanitation, Energy, Environment, Natural Resources & Climate Change and the Ministry of Agriculture, Livestock and Fisheries are the most relevant two ministries. All the departments are divided among the ministries. Also, there is the Governor's Delivery Unit (GDU) that is created to support the Governor in executing his Constitutional responsibilities and ensure that the Governor's development priorities are implemented effectively and efficiently (County Government of Isiolo, 2022a) Finally, Isiolo Municipality has its own board members (County Government of Isiolo, 2022b).

5.2 Hydrology in Isiolo River Basin

Isiolo County consists of mostly low lying flat plains. There are six perennial rivers in the county. The Merire River runs through Isiolo Town and is one of the tributaries to Isiolo River (Atkins, 2020). The exact area of examination in this report will be the Isiolo River Catchment, also known as the Isiolo River Basin. The Isiolo River Catchment is a sub-catchment of the greater ENN Basin, located on the foot of Mount Kenya. The Western Marania River and the Eastern Marania River have their upstream source in Mount Kenya, after which they converge into the Isiolo River, located downstream of the town of Isiolo (Republic of Kenya, 2013). The Merire river, which runs through Isiolo Town, also converges in the Isiolo River. The Isiolo River Catchment is delineated as shown in Figure 5.4 and Appendix D, the outlet being the Isiolo River, which connects the Isiolo River Catchment to various downstream catchments in the ENN basin. The catchment area is around 683 km^2 and the Isiolo River is approximately 95 km long, flowing from south to north. The highest altitude of the basin is 3905 meters and the lowest altitude is 872 meters (Republic of Kenya, 2013).

With regard to rainfall in the Isiolo River Basin, there are a couple of rainfall and discharge gauging stations. Monthly rainfall was observed from 1930 until 2011 by the JICA Team. The JICA Project team (Japan International Cooperation Agency) performs many research in Kenya and has written the National Water Master Plan 2030 among other things. The JICA team has observed the Timau Marania Station and the Isiolo DAO station, of which the locations are depicted in Appendix L.

For the Timau Marania Station, which is located upstream of the basin in the south of the Isiolo River Basin, the average annual rainfall was observed to be 959 mm per year. The average annual rainfall tends to be increasing with the years. The maximum annual rainfall during this period was recorded in 1998, with a rainfall of 1,883 mm per year. The heaviest monthly observed rainfall in the period 1930-2011 was 200 mm per month in the month November (Republic of Kenya, 2013).

Daily rainfall was observed from 1957 until 1989 and the maximum daily rainfall was observed on December 28 in 1983, with rain of 127.7 mm per day. Maximum daily rainfall of other observed years also mostly felt in the short rain season (10 times) and the long rain season (9 times). With regard to spatial distribution within the basin, the annual rainfall is higher in the upstream part of the basin than in the middle to downstream part. So in the mountainous area in the south of the river basin, it tends to have regional heavy rainfall. The rainfall in Isiolo Town is 600 mm per year on average and the observed maximum daily rainfall for a station near Isiolo Town for the period 1957-1989 is 97 mm per day on March 10, 1982 and the maximum annual rainfall is 1,261 mm per year in 1961 (Republic of Kenya, 2013). The maximum daily rainfall for both the Timau Marania and the Isiolo DAO station can be found in Appendix L.

With regard to flow, there is no water level data online available. There is however flow data from 1971 till 2011, where a peak flow can be observed of 364 m^3/s just upstream of Isiolo Town on 3/4/1981. However, peak runoff data during floods is not always included in this data set, since the measurements are only done two times a day and not specifically during a flood (Republic of Kenya, 2013).

The data sources of the gauging stations and the interpretation of such data of more recent years are further explained in chapter 7.

5.3 Geology of Isiolo River Basin

On the map of Isiolo River Basin and its elevation distribution, shown in Figure 5.4, it can be seen that Isiolo Town lays in a relative flat area and that the rivers originating from Mt. Kenya in the south are flowing towards the lower areas in the north. Upstream there are some slopes varying from 10% to 70 %. Downstream the river course is rather flat with a maximum slope of 2.5 % (Republic of Kenya, 2013). The longitudinal profile of the Isiolo River is presented in Figure 9.1, chapter 9.

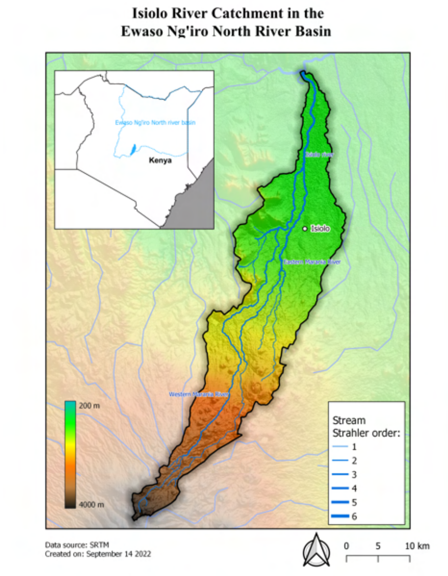


Figure 5.4: Isiolo River Basin delineation, height data obtained from the SRTM mission (Farr et al., 2007)

5.3.1 Soils

The soil distribution in Isiolo is highly influenced by its river basin. Clayey soils can be found all over the river basin, whereas sandy soils are more distributed at the left bank of the river. On the right side of the river catchment, some loamy soils are deposited. Downstream of the river and around Mt. Kenya highly clayey soils can be found. The city Isiolo is also located on a strong clayey soil (Figure 5.5). Because of this, in Isiolo Town, rainwater cannot seep underground and surface run-off occurs.

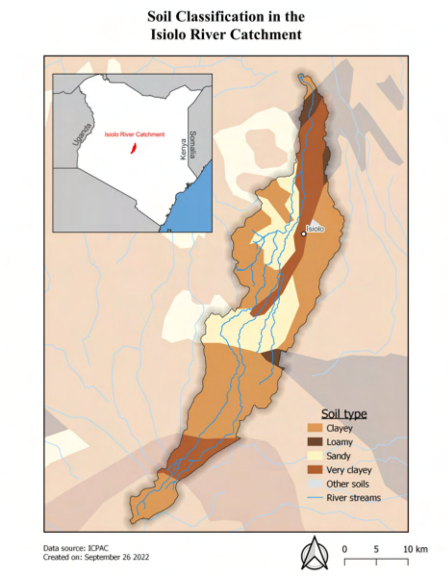
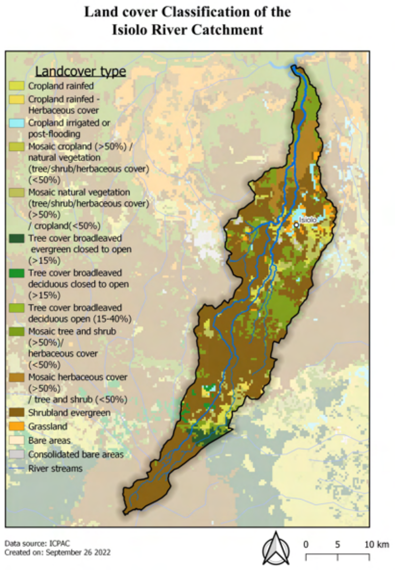


Figure 5.5: Soil distribution map of Isiolo River Basin

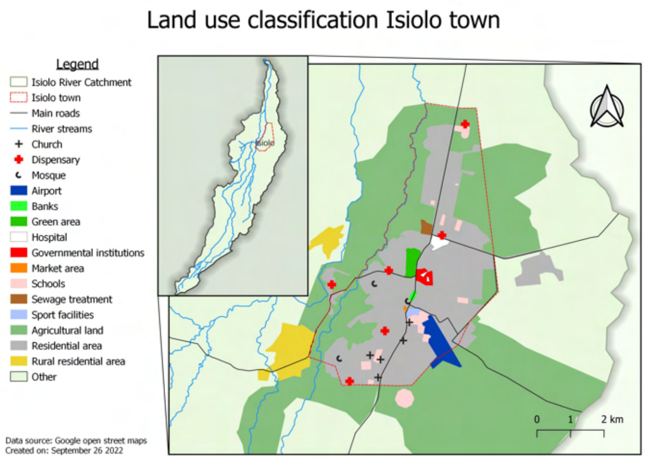
5.3.2 Land cover and Land use

The land cover of the Isiolo River Basin is shown in Figure 5.6a. Isiolo Town is located in semi-arid zone and is mostly covered with shrubland. This causes the water retention of rainfall water to be low which on its turn increases the risk of flooding. Upstream of the river, the mountainous areas are barren land and it can be seen that the forest area is extremely limited. As mentioned in section 3.3.1, deforestation is one one of the key threats to soils and can contribute to soil erosion. A more detailed land-use map of Isiolo Town can be seen in Figure 5.6b. Agricultural land is located along the Western and Eastern Marania River and in Isiolo Town.

The Merire River flows through the urban area of Isiolo Town. Furthermore, the locations of mosques, churches and other high value public buildings are shown on the map as these may be key buildings to protect against floods. A detailed explanation on how the natural conditions of the Isiolo River Basin affect inundation is given in section 9.1.



(a) Land cover of Isiolo River Basin



(b) Land use map of Isiolo Town

Figure 5.6: Land cover and Land use Isiolo

5.4 Water system in Isiolo

Because of a lack of sufficient funding, poor infrastructure development in urban areas in the Isiolo County is a big issue, including the development of water structures. In Isiolo Town there are serious problems in solid waste management, storm water drainage, and disaster management (Water Resources Management Authority, 2015). Because there is a lack of these infrastructures, the urban centers of the county (including Isiolo Town) can hardly play their roles in the economic transformation and social cultural integration. This limited opportunity for economic growth enhances even more obstruction in the infrastructure development (Aurecon AMEI Limited, 2020b). This section will discuss the current water system, including planned water structures.

There is not much documented about the current state of the water system Isiolo County and in Isiolo Town in particular, so therefore the most important information about the current water system (especially about the drainage system) within the town is been done with observations during a site investigation in the town. The results of achieved information can be seen in chapter 9.

Next to the drainage system within Isiolo Town another important part of the water system is the use of groundwater. Groundwater is the main water source for towns and settlements in the ENN basin, particularly from the Merti aquifer (Kuria, 2012). While the exact number of boreholes and shallow wells is unknown, up to 30 boreholes for a settlement is typically the amount of boreholes that serve a town or settlement (Government of Kenya, 2016). However, just a handful of these borehole have performed pump tests and for most of them the yield of water is unknown. Also, the amount of boreholes or wells exploited on private plots, hotels or offices is unknown.

To meet demand for water use, surface water is also used a lot in Isiolo Town. The Isiolo Water & Sewerage Company (IWASCO) relies on three water sources: the Isiolo River, the Ruguse river and groundwater through boreholes. IWASCO produces an average of 3940 m^3/d from all sources (Water Services Regulatory Board, 2018). IWASCO also states that in 2020 the production will be increased to 10.000 m^3/d, but it does not mention where this resource would come from. Interestingly, the demand for irrigation water is mostly met by surface water, namely 81% of total irrigation use. However, of all the groundwater also almost half of it is used for irrigation.

In the Isiolo County Integrated Development Plan 2018-2022 there is an overview of the water sources and access within Isiolo county (County Government of Isiolo, 2018). In the figure below one can see the sources of water during dry season and wet season. Most of the water comes in both seasons from boreholes and piped-water.

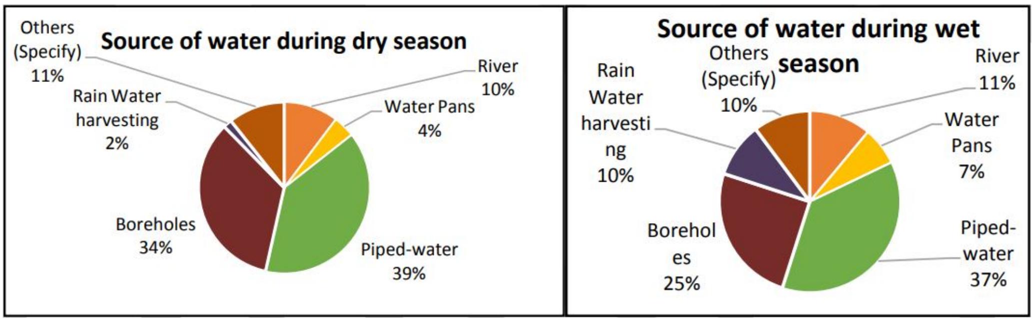


Figure 5.7: Sources of Water during the Dry and Wet Seasons (County Government of Isiolo, 2018)

The plan also states that in terms of spatial coverage over 175 (73%) of the villages rely on unsafe water and it is beyond a 5 *km* reach. Also up to 58% of the water sources are saline, which limits the availability of potable water, especially for human consumption. 59% Of the households are using drinking water from improved sources but only 12% are treating the water using improved methods. These disparities are higher in rural settings as compared to urban population with rural coverage estimated at 37% while urban coverage is estimated at 85%. One can assume that this is also the case for Isiolo Town which means better water quality is expected in Isiolo Town.

The expected growth in Isiolo Town and its growing water demands will result in a significant reduction in supply reliability. A key priority for the development of water resources in the ENN Basin should therefore concern improved water supply to the main urban centres through the provision of storage and intra-basin transfers. Currently there are no large dams, inter- or intra-basin transfers or hydropower installations in the ENN Basin (Aurecon AMEI Limited, 2020a). As a result, available storage is insufficient to mitigate the effects of droughts. The LAPSSET (Lamu Port-South Sudan-Ethiopia Transport) project, a mega infrastructure project as discussed in section 5.1, will increase future water demand along the LAPSSET corridor and specifically in Isiolo Town since this will be central hub of the project. The project will provide much employment in Isiolo Town and therefore the water demand is expected to increase especially there. There are dams planned to secure water supply in the future, as well as to manage floods. Dams that are planned to be constructed in Isiolo are (Aurecon AMEI Limited, 2020a):

- The Crocodile Jaw / Isiolo Mega Dam on the upper Ewaso Ng'iro River to harvest flood waters during peak rainy seasons and to supply water to the proposed Isiolo Resort City and to generate hydropower. It will provide a storage of 214 MCM and it will generate 40 MW.
- Archer's post, a large scale irrigation and water supply project. The Archer's Post Dam secures water supply and can therefore reduce the water stress in the county. It will provide a storage of 100 MCM and the dam also controls floods.

Besides construction of dams, Isiolo also plans other water management related measures. For example, there are already Sustainable Drainage systems (SuDs) planned for Isiolo Town and a big Biopark next to the Merire river (MetaMeta, 2022). In the Figure 5.8 below the proposed Biopark by MetaMeta for Isiolo Town can be seen. The Biopark is advised to be next to the Western Merire River. The proposed SuDs must intercept overland flows mainly alongside roads and passages (MetaMeta, 2022). The flows are conveyed through town and guided to the Marire River and the proposed to be built bio-park.

Figure 5.8: Illustrative design showing the bio-park during the rainy season (MetaMeta, 2022)

5.5 Flood aspects in Isiolo River Basin

Isiolo River Basin acknowledges four types of flood types. All these types occur in particular regions of the river basin and are accompanied by particular consequences which will be briefly discussed after the summation. The four flood types are (Republic of Kenya, 2013):

- Inundation in urban area
- Inundation which is caused by overflow and dyke break
- Debris flow
- Bank erosion

Inundation in urban area occurs in Isiolo Town and it disrupts transportation and economic activities in the urban area. Inundation caused by overflow and dyke break happen midstream and in the tributary stream of the basin and it causes damage of farmlands, infrastructure, and houses along the river. Debris flow occurs upstream of the Isiolo River Basin, so in the south of the basin, and it can damage water structures like bridges or farmland by burying crops. Bank erosion can occur in the whole basin and it can cause the arable top soil to be carried away resulting in infertile farmland. This type of flooding can also erode the access road to agricultural products or decrease the size of farmlands (Republic of Kenya, 2013).

The JICA Project team had conducted interviews within the whole Isiolo River Basin with different communities. The reported flood depth the communities mentioned ranged from 50 *cm* to 1.5 *m* centrally in the basin Republic of Kenya (2013).

Since 2012, most flood types have been inundation in urban area or inundation caused by overflow and dyke break. For example, a flood in 2012, September 25, was caused by a 20-minute heavy rainfall event with high wind. This resulted in inundation in the urban area, to a below-knee depth. Another flood, in October 2006, was caused by a broken embankment of the Isiolo River. This resulted in the death of 8 people and approximately 500 people were affected (Republic of Kenya, 2013). More recent studies about the latest floods are lacking, but will be looked upon in chapter 9, where the findings from the site investigation and gained information from questionnaires will be discussed.

5.6 Flood risk in Isiolo County and Isiolo Town

Just as the rainfall has a specific spatial distribution across the Isiolo River Basin as addressed in section 5.2, Isiolo County is divided with regard to the amount of annual rainfall. In the areas closer to the Nyambene Hills and the Mount Kenya, such as Isiolo Town, the annual rainfall amount is higher (Atkins, 2020). The risk of flooding due to among other things the rainfall can be visualized in a flood hazard map. These maps provide insight in the flood risk. For Isiolo County, which includes Isiolo Town, the figure below shows the incidence of flash floods. It shows the incidence of flash floods is high in Isiolo Town:

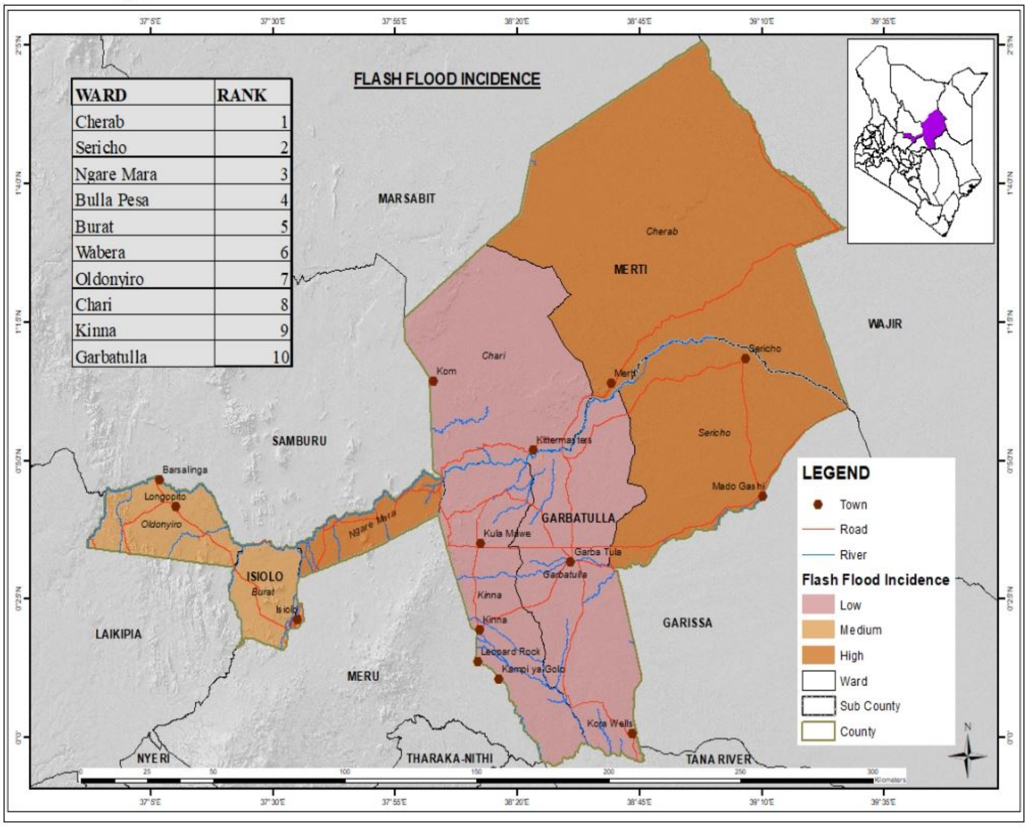


Figure 5.9: Flash Flood Incidence Map (Isiolo County Government et al., n.d.)

Flash floods are the result of extreme rainfall events which magnitude is expected to increase in the future as discussed in section 4.3. Isiolo Town is located in an ASAL region, so this is particularly vulnerable to flash floods. Besides, it is a flat area next to mountainous areas so the runoff is directed towards Isiolo Town. The incidence of flash floods is therefore found to be high in the hazard map. However, it must be noted that flooding can also have certain benefits in Isiolo County. Flood events can cause deposition of fertile silt on flood plains which can be used for flood irrigation, increasing water table levels and replenishing aquifers (Government of Kenya, 2016). Nevertheless, the flood economic exposure map shows an annual loss of GDP due to floods. The exposure map below shows this for Isiolo County:

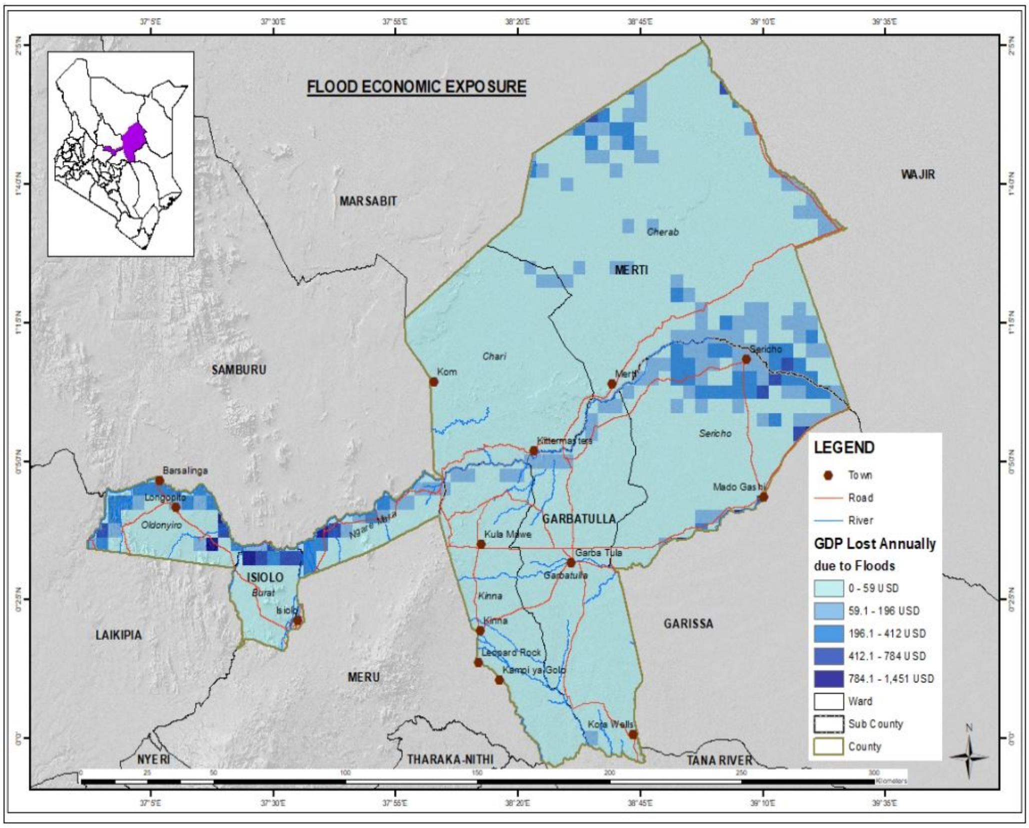


Figure 5.10: Flood Economic Exposure Map (Isiolo County Government et al., n.d.)

As visible in the figure, the economic exposure due to floods is very high along the Ewaso Ngiro River and near Isiolo Town. This indicates the negative impact of floods because the result of floods is a loss in GDP in the whole county, which shows the negative impact of floods is more dominant than the earlier mentioned benefits of floods. Since Figure 5.11 shows that Isiolo Town accounts for the vast majority of the population of the whole Isiolo River Basin, these presented flood hazard maps which include Isiolo Town already provide a good indication of the risk for the examination area.

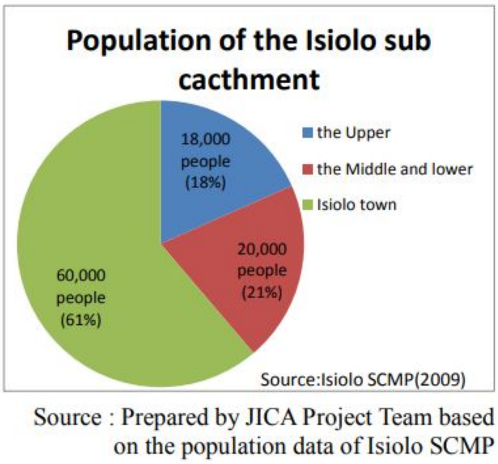


Figure 5.11: Population of Isiolo River Basin (Republic of Kenya, 2013)

Disaster risk is a result of both hazard and vulnerability or exposure. Vulnerability is related to social and economic aspects, like urbanization and environmental degradation. If a disaster risk is reduced, the probability of a hazard becoming a disaster is less. Disaster prevention measures can reduce the vulnerability of a community, resulting in less disasters or a reduction of the impact (Republic of Kenya, 2013). Flood hazard and flood risk can increase due to several reasons. The effect of climate change on the frequency of flooding was discussed in section 4.3. Besides the increasing risk due to climate change, poor agricultural practices in upstream land can reduce the local water holding capacity of soils. This can cause flash floods and soil degradation, including erosion, forming of deep gullies, and landslides. Also, if the water level in the downstream outlet rises, the backwater effect increases the risk of flooding. Other general causes for an increased risk of flooding are deforestation in the upstream part, silting of downstream river stretches, plants blocking the water flow, sedimentation and inadequate maintenance of a dam which increases the risk of a dam break, and increasing population with building near the river banks. Urban areas can also be affected by poor urban drainage (DRR - Team Kenya, 2019). These general hazards already form an indication of what can be hazards for the Isiolo River Basin specifically. Also, this section has provided an insight in the risks near Isiolo Town and Isiolo County with hazard maps. The specifics hazards and risk for the Isiolo River Basin and Isiolo Town in particular based on more literature studies and site investigations are discussed in section 9.1.

Chapter 6

SLAMDAM

The National Water Master Plan 2030 recommends to protect 21 specific flood-prone areas by river structural measures, whereof one of these areas is Isiolo as discussed in the previous chapter (Nippon Koei Co., 2013). The SLAMDAM can be such a structural measure. The SLAMDAM is a movable water-filled flood defence system, produced by SLAMDAM B.V. led by Zephyr Consulting. The inflatable dam is composed of a flexible material, which can be used in flood risk situations and can adapt to uneven surfaces. Technical details on the material properties and hydrostatical forces will be given in this chapter. Furthermore, other mitigation measures will be explained and a feasibility of mobile flood barriers will be given.

6.1 Material properties

The SLAMDAM is composed of the synthetic rubber Ethylene Propylene Diene Monomer (EPDM). This material yields high heat, ozone and weather resistance. This is important as these properties benefit the long life expectancy of the dam and gives it good storage properties. For the dam a two ply EPDM waterproofing membrane of 1.3 mm made of giscolene 130 MAX is used. This is internally reinforced with a high strength polyester scrim (SLAMDAM B.V., 2016). The material properties of the used EPDM are listed in Table 6.1. Key is the tensile stress the material can tolerate, which can be more than 800 N per 50 mm (Wikipedia, 2022).

Table 6.1: Characteristics of Giscoline EPDM (SLAMDAM B.V., 2016)

Property	**Eurocode**	**Value**
Thickness	EN 1849-2	1.3 mm
Straightness	EN 1848-2	$\leq$50 mm
Flatness	EN 1848-2	$\leq$10 mm
Watertightness (10 kPa)	EN 1928	Pass
Tensile strength (L/T)	EN 12311-2	$\geq$ 800 N per 50 mm
Elongation (L/T)	EN 12311-2	$\geq$ 15 %
Cold folding	EN 495-5	$\leq -50°C$
Resistance to UV exposure (1000 h)	EN 1297	Pass (Class 0)
Watertightness after artificial ageing (10 kPa)	EN 1296/ EN 1928	Pass

An important feature of the EPDM is that it does not pollute the water when used as it behaves neutral. The material can be produced in unique shapes due to its hot-bonding process with created seal as strong as original raw material. The thermal properties of EPDM are found in Table 6.2.

Table 6.2: Thermal properties of EPDM (Wikipedia, 2022)

Property	**Value**
Coefficient of thermal expansion, linear	$160\mu m/(mK)$
Maximum service temperature	$150°C$
Minimum service temperature	$-50°C$
Glass transition temperature	$-54°C$

From Table 6.2 it can be seen that the material can resist temperatures up to 150°C and as low as -50°C. This makes the SLAMDAM applicable in all possible climates.

6.2 Technical aspects

The robustness of the inflatable water-filled dam is determined by the hydrostatic forces on the SLAMDAM. The hydrostatic forces on the SLAMDAM are shown in Figure 6.1. The dam consists of two compartments, which are individually filled with water. The flood water, on the left of the dam, acts as a resulting force on the EPDM material. The water in the SLAMDAM is acting the hydrostatic forces on the material.

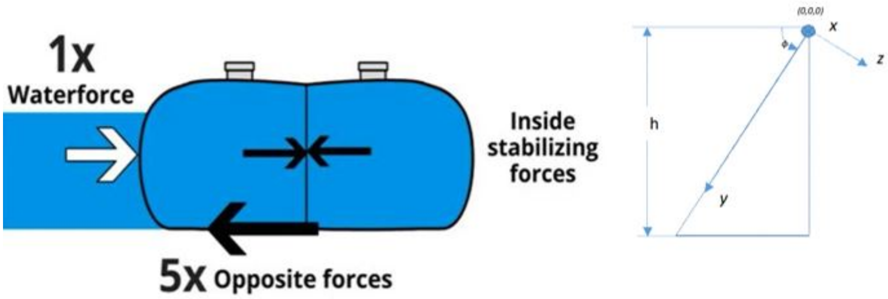


Figure 6.1: In and outside forces on the SLAMDAM (left) & geometric concept of the SLAMDAM (right) (SLAMDAM, 2016)

Because the SLAMDAM is used in flood situations, not only static forces apply but also hydrodynamic forces. These forces have an influence on the stability of the position of the dam. To determine this robustness, the normal force (F-normal) on the dam is calculated. Therefore the friction-constant between the surface, on which the dam is placed and the SLAMDAM needs to be known. The normal force and the friction coefficient will determine the horizontal resultant force of the SLAMDAM. This resultant force is then compared with the force from the flood water. If the horizontal resultant force is greater than the force from the flood water, the SLAMDAM will stay in place.

The total force or hydrostatic pressure of the floodwater can be calculated by taking the integral of the pressure over the area (A) of the dam (Equation 6.1). The pressure is composed on both the pressure of the static fluid at a certain depth and the dynamic pressure on the SLAMDAM:

$$F_{floodwater} = \int (p_0 + \rho g h) dA \tag{6.1}$$

$$= \int (p_0 + \rho g * y * sin(\phi) dA \tag{6.2}$$

$$= p_0 A + \rho g * sin(\phi) * y * A \tag{6.3}$$

With area A:

$$A = y * w \tag{6.4}$$

Here, w is the length of the SLAMDAM, h represents the height of the dam, ϕ is the angle of the side of the SLAMDAM, and y is the effective line. p_0 Is the atmospheric pressure and ρ is the density of the water. With the Equations the resulting force acting on the SLAMDAM can be calculated. The stress distribution in the wall of the SLAMDAM is shown in Figure 6.2. The wall of the dam has a thickness of 1.3 mm as this is a standard thickness of the EPDM suppliers. Th maximum height of the SLAMDAM can be up to 1 m.

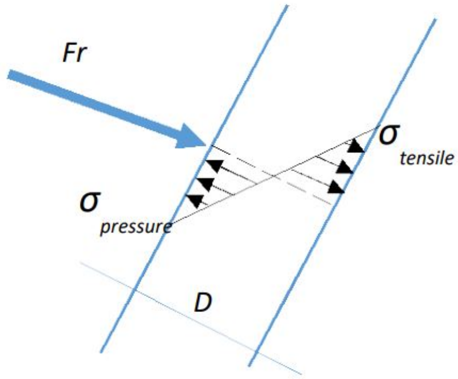


Figure 6.2: Stress distribution in the wall of the SLAMDAM (SLAMDAM (2016))

Together with the friction coefficient of the surface and the resulting forces on the outside of the dam as well as the forces inside the wall, the stability of the dam can be calculated. From experimental tests it is determined that the SLAMDAM can hold up to five times its weight in counter pressure and is therefore very stable, also when water overtops the dam (SLAMDAM B.V., 2016).

There are different SLAMDAM models available with corresponding dimensions. One compartment of Profidam L, which is the SLAMDAM used in this research, has a width of 200 cm, height of 100 $cm$and length of 500 cm. The retaining height is 75 cm (Figure 6.3). One unit of Profidam L costs €2300 and different units of dam can be connected as long as needed (SLAMDAM B.V., 2016).

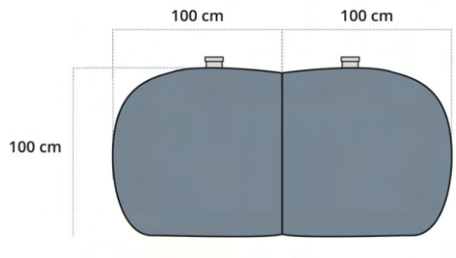


Figure 6.3: Dimensions of the Profidam L (SLAMDAM, 2016)

6.3 Benefits and challenges

Because of the mobility of the SLAMDAM, it can form a useful measure in unexpected situations. In this section other benefits and challenges of the dam will be discussed.

Other benefits of the SLAMDAM:

- The material from which the SLAMDAM is composed has a lifetime of at least 40 years, when properly used. This makes the dam a sustainable solution. The SLAMDAM is 100 % recyclable.
- Because the dam is inflatable, it can be easily stored at any location.
- The dam can be employed with a few people and filled with a waterpump. This reduces the man-power needed compared to for example using conventional sand-bags.
- Compartments of SLAMDAM can be connected up to 100 m length in a limited time. This makes it a quick solution in unexpected situations.
- Because of its concave shape, the force of the flood is acting under an angle on the SLAMDAM, which 'pushes' the dam towards the ground. This secures the dam in 'place'.

There are also some requirements for employing the SLAMDAM. When using the SLAMDAM, it should be considered that the dam needs to be placed on a flat surface. It cannot be placed on a slope, as this can cause the dam to move. The surface should also be clear from sharp objects so that the dam cannot be damaged. Also, no external forces, except for the flooding, may be applied on the dam when in use and the dam cannot be exposed to fire. Lastly, it should be considered that the water-filled dam is applying a load on the soil it is placed on. Therefore, the ground-conditions on which the dam is placed, should be examined. In Appendix E and F a guideline for using and storing the SLAMDAM can be found. A more social challenge is the vulnerability to vandalism. The material could be cut by people or vandalized if the community is not aware of the value of the SLAMDAM. Community engagement is therefore of importance. However, since the weight of the SLAMDAM when it is filled with water, the SLAMDAM is unlikely to be stolen.

6.4 Lessons learned from previous projects

The SLAMDAM has already been used in several projects before. There has been a pilot project in Burundi to demonstrate SLAMDAM as an effective solution to adapt to climate change by enhancing resilience and reducing vulnerabilities to floods and drought. Another project took place in Pakistan to lower the risk of floods in Gilgit-Baltistan. Lessons learned from these projects are that integrating the local community is important. They are the one who benefit from the dam and they need to manage and maintain the dam. If the local community is engaged the chance is also lower that vandalism occurs. Furthermore, it is important to visit the site where the SLAMDAM is advised to be deployed to make sure it fits the requirements. Modelling happens remotely but data can be wrong or incomplete.

6.5 Other flood mitigation measures

Other mitigation measures than the described SLAMDAM are also possible to implement. Besides structural measures, the National Water Master Plan 2030 also recommends non-structural measures since this can be more effective than structural ones which can be considered to have a limit effectivity against floods when exceeding a design level. Non-structural measures also have the advantage to generally be less expensive. Examples of human-related measures are hazard maps and an evacuation plan (Nippon Koei Co., 2013). This section will discuss some other possible mitigation measures than the SLAMDAM discussed before, both structural and non-structural.

6.5.1 Development of drainage systems

One key bottleneck in inundation in urban areas is the drainage system. Often drainage systems are old or outdated and not suitable for the current size of the paved urban area and its population size. As a result of this, there is bad sanitation condition after flood. A lot of damage can often be avoided by developing a drainage network in a town, since economic activity is often concentrated in the centre of a town. Possible improvement of drainage systems are cleaning of drainage channels, culverts, and side ditches of road to avoid blocking of the waterflow. However, the spreading effect of this measure is small and continuous maintenance is required, so sustainability is poor. Also, this measure requires a long term plan, because preparation work takes long (Republic of Kenya, 2013).

6.5.2 Excavation or widening of a river bed

Overflow of a river can be due to a small cross section. A small cross section can be insufficient for a river flow as a result of a high intensity rain event. To prevent future overflow from a river, one can excavate a river to create a larger cross-section and therefore a higher flow capacity for water. Depending on the size of the excavation this would cause a decline in overflow from the river and with that a decline in damages done by inundations. One should however note that due to the amount of deposit from sedimentation upstream this causes that excavation needs to happen multiple times so this solution can become very expensive. Another demerit is that preparation needs long term.

Besides excavation one could also widen a river. This could help improve the flow capacity as well. An extra demerit of widening instead of excavating is that this measure would take even more time as there can be (il)legal housing close to the river and possible resettlement could occur if this mitigation measure is chosen as a suitable option. For both excavation and widening, both costs and effectiveness are extensive (Republic of Kenya, 2013).

6.5.3 Retarding basin or Pond

Peak discharges from flood events can have disastrous effects in the urban context. A retarding basin can help flatten the hydrograph of the runoff by creating a buffer for water storage. Lower flow means less energy being exerted by the water on its surroundings, resulting in less damage by erosion (Melbourne Water, 2021). Retarding basins are most effective in areas with limited elevation differences, and are typically characterized as low lying areas of land which can store large volumes of stormwater. Retarding basins need a large surface area to be effective.

Despite proving to be effective in reducing the peak flows of a storm, there are various disadvantages to the implementation of this mitigation measure. First of all, construction/ excavation of a basin can become quite costly as the meticulous planning and design required to implement the basin contribute to the high expenses. Also, the large scale of the mitigation measure requires an Environmental Impact Assessment to be made because the implementation requires excavation of large areas of land as well as the use of heavy machinery. But overall, the effectiveness of the basin is high in the urban context and maintenance of the basin is not expensive (Republic of Kenya, 2013).

6.5.4 Infiltration areas

Another possible mitigation measure is green solutions, which is adding more infiltration areas. There are different versions but they all have the same purpose: to delay, use, capture or absorb rainwater instead of having the rainwater fell onto impervious surfaces that leads to more overland flow. So the focus is not on draining water, but rather on letting the water infiltrate into the ground, therefore reducing the runoff. Therefore there is less runoff of the water into the drainage system, meaning that the system will be less overloaded during a rainfall event. A number of examples of infiltration areas are:

- Sustainable drainage system (SuDs)
- Bioswale / Wadi
- Bio-retention area (Bio-park)
- Green roofs
- Wetlands
- Rain gardens
- Permeable pavements

However, it must be noted that infiltration areas solely will not be sufficient in managing the extreme rainfall events (Atkins, 2020).

6.5.5 Sandbags

One of the most known measures for a temporary flood mitigation is the sandbag. It is mostly a measure which is used in case of an emergency like a flood since its preparation period is short. It can also be used for domestic use to close the gaps of doors and other parts of houses to prevent water coming into the house (Zaalberg, Midden, Meijnders, & McCalley, 2007). A sandbag is a bag filled with sand and when constructed with multiple bags together it forms a small dam, creating almost water tight barriers to obstruct flow of water and sand. If there is a lack of infrastructure it is a simple measure to implement as it does not need preparation beforehand, except of the filling. Besides, the measure is inexpensive, maintenance is simple, and application in other areas is possible. A demerit is that the barriers can take quite some time to be built and it is very labor intensive since it is only effective with a large amount of sandbag. Next to this it is impossible to prevent floods to be completely prevented as water will always leak between the bags (Republic of Kenya, 2013). The sandbag has 4 types of 'flood failures', which can be seen in Figure 6.4 (Lendering, Jonkman, & Kok, 2016). The 4 types of failure are (Boon, 2007):

- Overflow
- Sliding
- Rotation
- Seepage

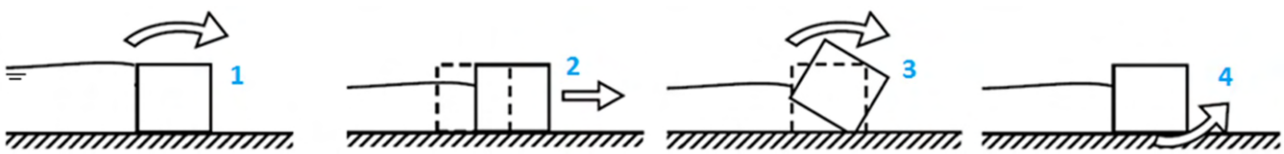


Figure 6.4: The 4 types of flood failures for sandbags (Lendering et al., 2016)

6.5.6 Forestation

Forestation is also a possible measure against floods since it increases the storage and it is inexpensive. Forestation can cause many environmental positive impacts and a big increase in water storage will occur. However, the growth of trees takes time and the measure should be implemented in a very wide scale to be effective in reducing sedimentation upstream and it can take a couple of years to see the first effects of this mitigation measure, and that is if the vegetation is maintained well. Also, the downside of forestation can be the climate, since the climate needs to be supporting tree growth. For example, a tree needs to be able to cope with long periods of drought (Republic of Kenya, 2013).

6.5.7 Flood Early Warning System (FEWS)

The forecasting of floods is one of the mitigation measures that does not necessarily prevent flooding. However, it can prevent a lot of damages and deaths due to flooding. The goal of this measure is to present and disseminate information about upcoming floods. FEWS is an inexpensive system that can transmit information about a flood that will occur in an area due to hydrological data it is measuring upstream. If a certain amount of rainfall occurs or a certain water level or discharge in a river is met the system can forecast the type of flood that could happen. If certain (area specific) conditions are met, these systems can send out a signal that a flood is likely to occur. It does depend on with systems are used. One could use a rain/discharge gauge network, rainfall radars, weather forecasting, satellite data, local measurement data or even horological model (Cools, Innocenti, & O'Brien, 2016). Because of the warning people can better prepare for upcoming floods. The community is able to evacuate in time due to the warning or built up other emergency measures. FEWS are often accompanied by evacuation plans for areas known to be prone to flooding. However, it is mostly effective when people are aware how to react to such a warning. Therefore, educating the community is also of importance. Besides, cooperation between upstream and downstream is of importance (Republic of Kenya, 2013).

6.5.8 Flood Hazard Map

Flood hazard maps are maps that based on numerical analysis. These maps should show what areas will have inundation during certain rainfall-events and what evacuation routes can be taken in case of need. Making these maps is not costly, however the formulation of making these maps and the correct usage of software and data is of high importance. Educated hydrologist can make this map, but the changing surroundings of land causes that these maps needs to be updated every once in a while. With these flood maps these maps can help with the future planning of urban areas. For example, if it is clear that on certain areas inundation will occur often these areas can be planned for accordingly, e.g. using proper mitigation measures on such places. The outcome can also be that no residential/agricultural land is built on such areas which are vulnerable to regular inundation. With this in mind these maps cannot only prevent damages, but also help in land use planning and mapping where other mitigation measures are recommended to implement (Republic of Kenya, 2013).

6.6 Feasibility mobile flood protection systems

Just like the previously discussed sandbags, the SLAMDAM is a mobile flood protection system. To indicate whether the SLAMDAM is feasible in the Isiolo River Basin and how it performs in comparison with other flood mitigation measures, it first needs to be established where and how in flood risk management the SLAMDAM would perform. A report about mobile flood protection systems offers an overview of the different possible types (Koppe & Brinkmann, 2010). This overview is shown in the following figure:

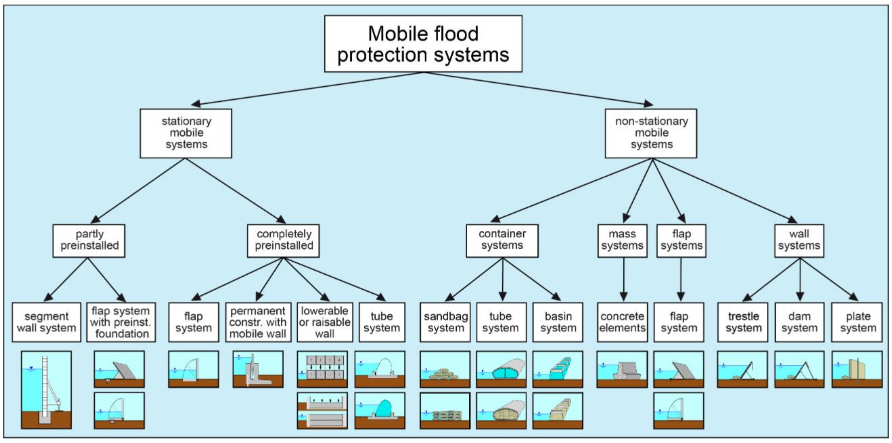


Figure 6.5: Overview of mobile flood protection systems (Koppe & Brinkmann, 2010)

It can be seen that mobile flood protection systems differ in material, construction, available protection height, and permanent facilities (Koppe & Brinkmann, 2010). The SLAMDAM falls under the container "tube" systems and is in direct competition with sandbags.

For flood prevention, mobile dams might not seem to be the first choice, as permanent flood defenses offer high protection against floods and that do not require much maintenance. However, in densely populated areas, or areas in which buildings are built close to the flood plane and little space is available, mobile dams such as SLAMDAM could form a solution (Koppe & Brinkmann, 2010). A mobile barrier could also be used to heighten a permanent flood defence systems at risk of overtopping. Also, a mobile barrier can be used as to bridge the time until a permanent flood protection structure is built. A drawback of mobile flood barriers is their limited height, which is not suitable for all flood events.

Additionally, it is important to minimize the effects of floods at an early stage through land use planning. The mobile barrier can be taken into account in land use planning, for example when it is not possible to widen the river to increase its flow capacity because of the value of buildings next to the river.

Finally, as emergency response, mobile flood barriers take in an important role. The suitability of the mobile barrier depends on its logistic features such as transport and installation time. Currently conventional sandbags can be used as emergency response in flood defence situations, but this is time-consuming as the bags have to be filled by sand, transported and then built up. Many men are needed because many sandbags are required to prevent an area effectively against flooding. The SLAMDAM mitigates these drawbacks by using water to create the defence. Because of the light weighted material it can be placed with a few people in a short time frame. However, water availability to fill the dam, needs to be assured.

Chapter 7

Method

This chapter discusses the method which is used to come up with the results which are provided in the upcoming chapters. The utilized software will be discussed and the equations which are used to provide input for the tools will be given and explained here as well. Besides, the already used literature study and other methods which were used during the 8 weeks will be discussed.

7.1 Literature study

To come up with results, a literature study is done to be provided with the most recent information about floods and other related aspects in the location of interest. This literature study provides all the relevant information to use in the tools and to come up with suitable recommendations. The required background information to come up with and to support the results which are given in the next chapters, is already provided in the previous chapters. Most information was retrieved from governmental reports, often made by consultancy parties originating from other countries commissioned by the Kenyan Government. One important report which is referred to a lot is the report made by the JICA Project Team: the Isiolo River Basin Integrated Flood Management Plan. This flood management plan contains much relevant information for this report since it is about the same river basin.

7.2 Case study Isiolo River Basin

To check the feasibility of the SLAMDAM by using several tools of which the way of operating will be discussed in section 7.7 of this chapter, it is desired to zoom in on a particular delimited area since this will result in the most accurate recommendation in the limited amount of time of 8 weeks. So by focusing on a particular area, the best suitable and most specific advise can be given. The reason for the Isiolo River Basin specifically has been discussed already in the previous chapters. The case study includes a literature study about Isiolo in specific to find out the current state of flood-related aspects and a site investigation. During this site investigation the flood risk will be assessed. Also, the designated suitable sites to implement the SLAMDAM as outcome of the modelling beforehand will be examined with regard to the underground and other aspects like the presence of water which have to be taken into account when considering localising the SLAMDAM. Besides, interviews will be conducted with the more regional parties, including the local community like farmers. This is because the SLAMDAM also involves community engagement to deploy the SLAMDAM in times of need.

7.3 Stakeholder mapping

Water resources management is nationally as well as regionally regulated. To understand the regulation of Kenyan flood risk management and also the management in the Isiolo River Basin specifically, the stakeholders are mapped. The stakeholder mapping also involved explaining important laws, policies, and plans from various parties. This is done to understand the context in which the SLAMDAM and FIS Tool will be used. This allows to see where the new technologies fit well or where it might encounter any residual risks or obstacles. A formal chart is used to map the institutional framework and interrelationships with both government agencies and other stakeholders. By focusing on understanding the characteristics of social networks and considering a range of perspectives, the likelihood of collective action and successful project management is increased (Richards, Carter, & Sherlock, 2004). It will also clarify how to approach different stakeholders and which stakeholders are important to include, for example, in the decision-making process for implementing the SLAMDAM and the FIS Tool (De Bruijn & Ten Heuvelhof, 2018).

7.4 Interviews and visitations

Several organisations are visited and interviews are conducted with several parties to gather information and knowledge. The main purposes were to collect data which would be used as input for the software, to get a better understanding of the Kenyan and Isiolo context and to collect the challenges they experienced during project management of flood risk mitigation.

The involved parties are: the Water Resources Authority (WRA), Netherlands Development Organisation SNV, the embassy of the Kingdom of the Netherlands, National Drought Managament Authority (NDMA), and the clients Zephyr Consulting and Nelen & Schuurmans. Interviews are also conducted on a more regional level. The following parties are visited and/or interviewed: Water Resources Users Association (WRUA) Isiolo, WRA ENN basin area Regional Office, WRA Isiolo, NDMA Isiolo, and Centre for Training and Integrated Research in ASAL Development (CETRAD). The Kenyan Meteorological Department (KMD) has also been contacted via e-mail to get data. Table 8.1 provides an overview of all the interactions with stakeholders during interviews, site visitations, and demonstrations.

As mentioned a part of the interactions with the stakeholders is collecting challenges from stakeholders experiences in project management in Kenya. In Figure 7.1 the framework that will be used to structure the challenges is shown. The challenges will be written down as mini-stories and by using open coding the mini-stories will be collected. Open coding, axial coding, and selective coding are all steps in the grounded theory method of analyzing qualitative data (Khandkar, 2009). It basically works as follows: open coding is when you split the textual data into separate parts, during axial coding connections between the codes are made, and by selective coding the one central category that connects all the codes in the analysis is selected (Khandkar, 2009). In chapter 8 an overview of all the mini-stories including potential solutions and the coupling of mini-stories to categories is presented.

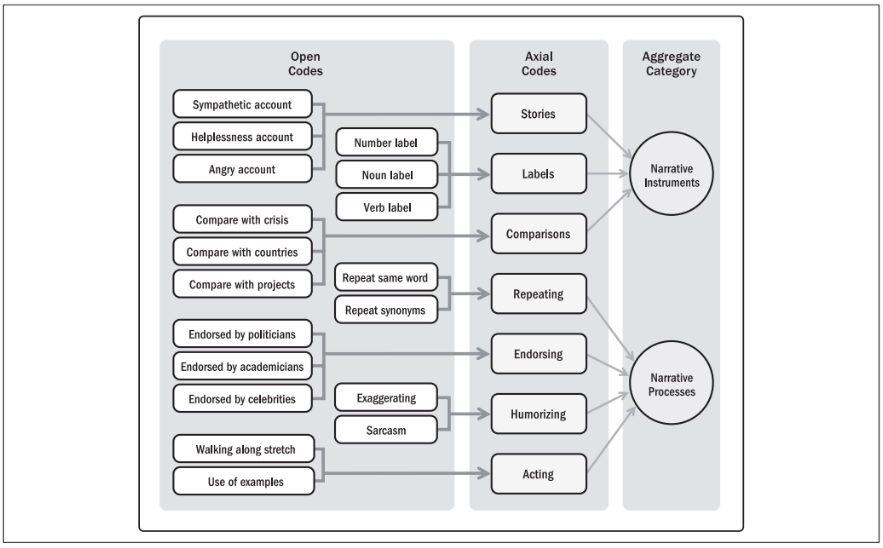


Figure 7.1: Coding pattern (Ninan & Sergeeva, 2022)

Finally, during the site investigations the local communities will be asked questions about their experiences with floods. This is done to better understand the local context and to validate the available data. The list of questions can be found in Appendix G.

7.5 Data collection

There are various data sources on the Isiolo River Basin. How useful the data is depends on the resolution, the accuracy, and the reliability of the source as well as how up to date the data is. Out of all the available data, a selection has been made based on the previously mentioned criteria. Some of the data is publicly available such as height-elevation data from the SRTM space mission (Farr et al., 2007), whilst others had to be personally requested at an entity owning the data such as rain gauge measurements within the Isiolo River Basin. Appendix H contains a list of all the acquired data and their sources, as well as an explanation on the selection of such.

7.6 Gauge Measurements

7.6.1 Stream gauge measurements

From the 5D08 ISIOLO stream gauge, provided by the WRA ENN basin area Regional Office in Nanyuki, measurements for the discharges are given. This data set contains monthly measurements of the Isiolo River during flooding seasons. The measurements are from the year 1976 until 2013. The pitfall of this data set is the fact that only one measurement per month is performed, making it difficult to estimate the flood peak runoff after a certain rain event. It could be that the measurement is done on an irrelevant day with regard to the flooding situation of the season. Furthermore, there are some gaps in the data. Nevertheless this data can be used to validate the 3Di schematisation and set initial boundary conditions for the model. Besides the river discharge, the flood peak runoff can be estimated using a previously formulated rational formula by the KMD, supported by the JICA.

To calculate the flood peak runoff with the rainfall measurements from several gauging stations from 1957-1989, the Rational Formula can be used (Republic of Kenya, 2013). This formula is:

$$Q = \frac{1}{3.6} * f * r * A \tag{7.1}$$

Where: Q = discharge (m^3/s), f = coefficient of discharge (-), r = average of rainfall intensity within arrival time of flood (mm/h), A = dimension of river basin (km^2).

Another relevant aspect with regard to the stream is the flow capacity of a river. The following Equation can be used to determine the flow capacity of the river (Hoes, 2022):

$$Q = k * A * R^{2/3} * i^{1/2} \tag{7.2}$$

k is the Strickler Coefficient ($m^{1/3}/s$) and it is dependent on the roughness. The higher the coefficient, the less roughness so the smoother the river bed. The Strickler Coefficient is depend on the vegetation and depth, where vegetation is again dependent on the season. Therefore, there is a distinction between summer and winter, which is visible in the Table 7.1 below (O.A.C Hoes and N.C. van de Giesen, 2022):

Table 7.1: Some values for the coefficient Ks in the Strickler formula. A small waterway is defined as a waterway with a maximum depth of 80 *cm* and hydraulic radius of 50 *cm* (O.A.C Hoes and N.C. van de Giesen, 2022).

Watercourses	Summer	Winter
Small waterway with light soils	35	35
Small waterway with heavy soils	25	25
Medium-sized waterway with light soils	40	30
Medium-sized waterway with heavy soils	30	20

Furthermore, R (in m) Is the hydraulic radius which is equal to the area A (in m^2) divided by the wetted perimeter P (in m). P and A are both dependent on the shape of the cross-section of the river. Lastly, i is the hydraulic gradient (-).

7.6.2 Precipitation gauge measurements

With data of maximum daily rainfall one can calculate the expected daily rainfall for events with different return periods. There are two methods of extreme value analysis used to perform this calculation: Peak Over Threshold (POT) and Annual Maxima (AM) (Hoes, 2022). These methods can be used to calculate the return periods of a certain rainfall amount or the amount of precipitation for a certain return period. This report will calculate the expected daily rainfall (X) for a given return period given in years (T) since the resulting rain intensity is the input for the software 3Di.

The rainfall gauge measurement data are from the Isiolo River Basin integrated Flood Management Plan, performed by the JICA. They have used data from the Timau Marania Station and the Isiolo DAO station in this flood management plan which are retrieved from the KMD (Republic of Kenya, 2013). The KMD has again been contacted for this particular report with the request for more recent data. However, the KMD has responded via e-mail that there are currently no rainfall gauging stations in operation within the whole Isiolo River Basin. More specifically, the rainfall gauging stations of interest for the Isiolo River Basin which were also used by the JICA team are out of running for at least 10 years now. Therefore, the most recent data is retrieved from the Trans-African Hydro-Meteorological Observatory (TAHMO). The complete received data set from the TAHMO was precipitation data from the period 01-09-2017 until 01-09-2022 for 5 measuring stations including and surrounding Isiolo Town. These measurement stations are all located at school ground and are for education purposes and it aims easy access to rainfall data (van de Giesen, Hut, & Selker, 2016). The station of most interest is the one is Isiolo Town since this is located near the Isiolo DAO station which was used by the JICA team, so comparisons can be made. The specific locations of the stations and the associated data sets are referred to in the results, in chapter 9, section 9.3.2.

Annual Maxima

The AM-method uses the maximum daily precipitation in a year as input. The outcomes of the method depends on the amount of input and thus years, so data from a sufficient amount of years is required.

The formulas for Annual Maxima are (Hoes, 2022):

$$F(x) = exp(-exp(-(\frac{X - X_0}{\beta}))) \tag{7.3}$$

$$T = \frac{1}{1 - F} \tag{7.4}$$

$$\beta = \frac{\sigma * \sqrt{6}}{\pi} \tag{7.5}$$

$$X_0 = \mu - 0.5772\beta \tag{7.6}$$

Equation 7.3 to 7.6 will result in:

$$X = X_0 - \beta * \ln(-\ln(1 - \frac{1}{T}) \tag{7.7}$$

Where:

- T = Return period in years
- X = the expected daily rainfall in mm/day
- μ = the average of the Annual Maxima daily precipitation
- σ = the standard deviation of the Annual Maxima daily precipitation

Peak Over Threshold

POT is desired when the amount of years of available data is insufficient to use the Annual Maxima method. By chosing a threshold for a certain amount of precipitation, there are more data points included in the calculations since all values above this threshold are used. Defining the threshold is one of the main challenges of the POT method because the selection of the threshold is subjective (Bezak, Brilly, & Šraj, 2014). According to (Lang, Ouarda, & Bobée, 1999) it is important to select a threshold value that is high enough, so that the model assumptions are not violated. But the truncation level should be as low as possible so that more reliable parameter estimates can be used.

For this report two options to select the threshold (ϵ) are being used:

1. Langbein method

According to (Langbein, 1949) it is best to select the threshold to be equal to the lowest Annual Maximum. In other words, from every year of data the maximum daily precipitation is filtered. The threshold is the lowest maximum value from all the years. This means that at least one event per year is included in the analyses.

2. Madsen method

The other method is developed by (Madsen & Kundzewicz, 1993), who suggested to use formula 7.8 to calculate the threshold. This method uses data properties from the whole data set to calculate the mean value (μ_x) and standard deviation (σ_x). Next to this they use the standard frequency factor k. This frequency factor k is based on the Flood Estimation Handbook (Robson & Reed, 2008) and is chosen to be 3 (Madsen & Kundzewicz, 1993). This low k value means a that a low threshold value is selected and more events are included.

$$\epsilon = \mu_x + k * \sigma_x \tag{7.8}$$

Where:

- μ_x = Mean values (of all data)
- σ_x = Standard deviation (of all data)

- k = Standard Frequency Factor

These obtained threshold values can be used in the Peak Over Threshold fomulas. The formulas for Peak Over Threshold are (Hoes, 2022):

$$F(x) = 1 - exp(-\frac{x - \epsilon}{\beta}) \tag{7.9}$$

$$T = \frac{1}{1 - F(x)} * \frac{N}{n} \tag{7.10}$$

$$\beta = \frac{1}{n} \sum (X_i - \epsilon) \tag{7.11}$$

Equation 7.9 to 7.11 will result in:

$$X = \epsilon - \beta * \ln \frac{N/n}{T} \tag{7.12}$$

Where:

- ϵ = the selected threshold in mm
- T = Return period in years
- X = the expected daily rainfall in mm/day
- N = the number of years of available data
- n = the number of data used for POT calculations above threshold
- μ = the average of the Annual Maxima daily precipitation
- σ = the standard deviation of the Annual Maxima daily precipitation

Important to notice is that the return period in the POT method needs to be corrected for using more values than the given amount of years. This is because POT gives an overestimation of the return period so the result of the return period must be multiplied by the number of years (N) divided by the number of used data points (n), which is already included in the provided Equations above.

The rainfall in mm/day for certain return periods can be converted to an intensity in mm/h when considering the duration of a rain event. This conversion is necessary because the input of 3Di is an intensity in mm/h, which will be elaborated in the next section. Flooding is often the result of high intensity, short duration events or low intensity long duration events. Therefore, two duration lengths are looked upon, namely 1 hour and 3 hours, where a duration of 3 hours will result in a lower intensity.

7.7 Software

To assess the applicability of the SLAMDAM in the Isiolo River Basin, hydrological models and various software are required. The performance of the SLAMDAM can be backed up by models and software provided by Nelen & Schuurmans. 3Di models the waterdepth as a result of a rainfall event. Flood Intelligence Service (FIS) provides a cost-benefit analysis of different flood mitigation measures. QGIS is used to gather data such as digital elevation maps, catchment delineation, land cover, and rainfall distribution to use as an input for the models in the 3Di and the FIS Tool. The tools are used to pinpoint where exactly a SLAMDAM is desirable to be deployed.

7.7.1 3Di

Estimating the water depth distribution after heavy precipitation can be done using hydrological models. The measurements provided by the gauging stations described in section 5.2 represent the input of a hydrologic model which will represent the hydrologic response of the Isiolo watershed to various sources of forcing. Hydrological models are a powerful tool to represent such responses of catchments. Formulating hydrological models aids to help in understanding the interactions between different hydrological processes. By knowing how these processes have behaved in the the past, the behaviour in the future in different scenarios can be predicted. With the upcoming threat of increased risk of flooding in the Isiolo watershed, predicting the response of its hydrological system to variable (extreme) weather conditions enables to find the right approach as to mitigate flooding in the future.

There are various ways to formulate and represent hydrological models. The Isiolo watershed can be seen as a system of several buckets connected to one another. Each bucket contains its own properties and response to the forcing it experiences. This so called TANK-model provides a simplified description of the hydrological cycle to imitate a natural system (Al-Asadi, Abbas, & Hamdan, 2020). While the TANK-model method is a common approach to solve water flow, 3Di makes use of computational (sub)grids and physics based equations to compute the flow of water numerically. The predefined grid space allows for computation of different surface water and groundwater domains (as well as 1D elements). The state of water in each of these domains is computed after a certain time step, in this way both space and time are discretised and numerical calculations are made possible (Nelen & Schuurmans, 2022d). To optimise the computational cost of the model, grid refinements can be performed in key areas where high order of detail is required. This results in a staggered 2D grid with varying cell sizes (see Figure 7.2). The centre of the cells define the water level and water pressures, while the edges of the cells define the water velocities. Conservation of volume and momentum are used to make the hydrodynamic computations, documentation on the formulation of the concerned computations can be found on the 3Di documentation on the 3Di website.

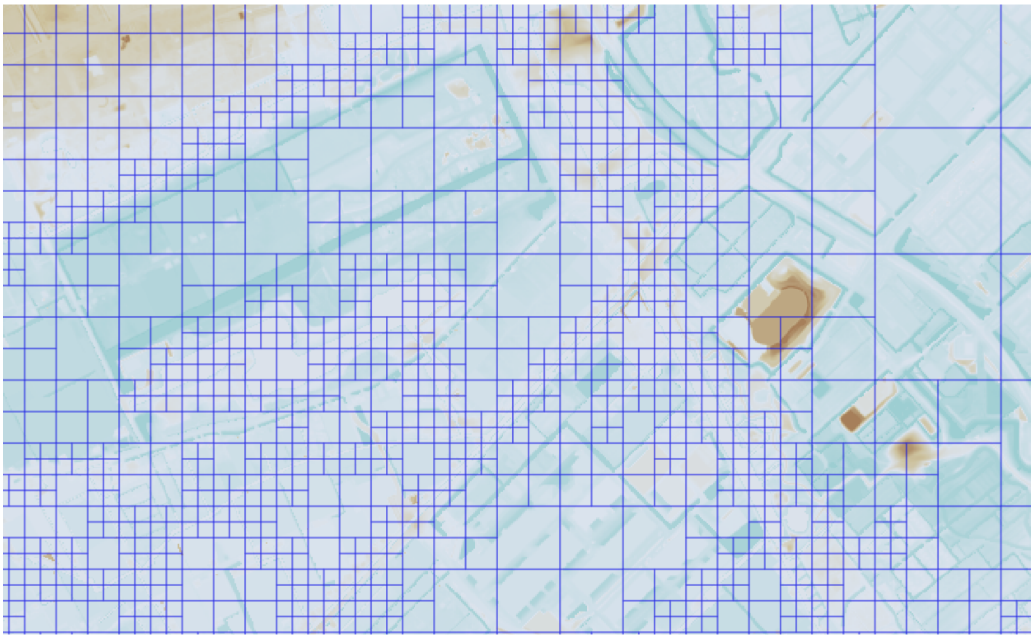


Figure 7.2: Example of computational grid with refinements (Nelen & Schuurmans, 2022d).

Nelen & Schuurmans has developed their own hydrodynamic modelling software to simulate the response of a water system to e.g. increased rainfall, higher river discharges, and sea level rises. The numerical model is formulated in this software. This software has been provided for use in predicting the impact of flooding on the Isiolo River Basin. The benefit 3Di offers is the ability to interactively model a catchment and its response. Examples of these are changing pump characteristics, land cover type, external forcings and failures in the urban or rural water system (Nelen & Schuurmans, 2022b).

The 3Di software is accessible via a web browser, which makes it possible to run complex simulations remotely without requiring a device with high computational power. The model and its properties or boundary conditions can be added from the livesite and is sent to a remote computer server which runs the simulations. During the run of the simulation it is possible to pause and modify the settings of the model. The 3Di Ecosystem is built open its own developed Application Programming Interface (API), which makes it possible to connect 3Di to other programming environments (Nelen & Schuurmans, 2022a).

To be able to run a hydrodynamic model using the 3Di software, input data is required. For the case of the Isiolo River Basin the rainfall data, the catchment boundaries, the height elevation within the boundaries, and the land use/land cover within the catchment are required. This data can be generated with input from a QGIS environment, or programming software such as Python or Matlab through the API which 3Di runs on (Nelen & Schuurmans, 2022c). Section 7.7.3 will further discuss QGIS. The land cover of the catchment is relevant in determining friction factors which influence the preferential flows through the system, as well as any possible water storage in the subsurface. In cases of there being a highly variable topography, meaning a catchment with large elevation differences, water flow will mainly be driven by gravity, and influences from land cover and subsurface storage can be omitted. Furthermore, dry areas such as the Isiolo River Basin contain relatively dry soils, with limited storage capacity. Modelling the Isiolo River Basin without a land cover classification can still provide accurate results. However, being in possesion of such would help in obtaining the most realistic results (Nelen & Schuurmans, 2022c).

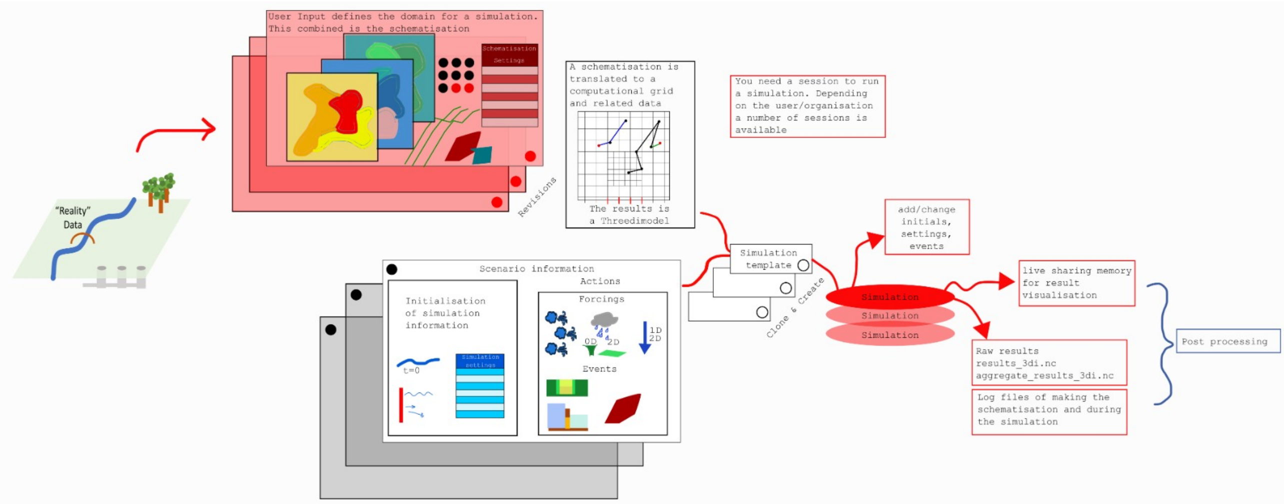


Figure 7.3: 3Di workflow and modelling concepts (Nelen & Schuurmans, 2022c)

Once all input data has been collected and put in the model, several scenarios can be run in the software. These scenarios are defined by 4 factors:

1. External forcing
2. Events (i.e. breaches, failures etc.)
3. Initial conditions
4. Simulation settings (i.e. numerical and time step settings)

Each scenario can be saved to be run again at a different moment. Once the simulation has finished running, the results are saved and can be downloaded for analysis. By saving previously drafted scenarios, changes in the simulation factors can be compared to one another (Nelen & Schuurmans, 2022c).

7.7.2 FIS Tool

The Flood Intelligence Service (FIS) is a tool developed by Nelen & Schuurmans for Zephyr Consulting. It aired in August 2022 and this research is one of the first projects which uses this tool. The FIS Tool works just like 3Di on an online server which performs all the calculations. Therefore a computer does not need to do a lot of computing, however a stable internet connection is preferred.

With the water depth distribution from 3Di one can calculate in the FIS Tool the amount of damages and casualties a flood has on a certain area. These 'Initial' damages can be divided in the following subjects:

- Residential damage
- Agricultural damage
- Affected people (number of people)
- Affected residential area (in m^2)
- Affected agriculture area (in m^2)

Next to calculating the amount of Initial damages, one can also measure damages of the same area when a mitigation measure has been implemented. For example if one would like to protect a certain area with a small dike, this dike can be used as input in the FIS Tool. The input would be created as an shapefile using QGIS (see 7.7.3). When this measure and its height has been given as input, the FIS Tool will give the so called 'Measure' damages besides the Initial damages. Which, provided that the mitigation measure has been implemented well, should cause lower damages than the Initial damages. The difference in the Initial and Measure damages is called the 'Benefit' damages. With this difference the potential of a mitigation measure can be shown in the area.

The data one can implement in the FIS Tool has a big impact on the amount of damages the tool will calculate. If no additional or personal retrieved data is added then the tool uses some standardized data in the baseline settings. These data include:

- Water depth data
- Damage curves (per country)
- Land use 2021 (ESRI) map
- Global population

Some of this standarized data can be replaced with other data. The water depth data is currently only from global rivirine floods (from 1-in-10 to 1-in-500 years) (Dottori et al., 2016), but can be replaced with a water depth file from rainfall events using 3Di. The standard land use map data is from the Environmental Systems Response Unit (ESRI) 2021 (ESRI, 2022), which is a global data set. For more accuracy, a local data set is preferred. The global population data is from Meta Platforms Inc, which has a very accurate way to see how many people are in an area due to the activities on their software (Facebook, Whatsapp, Instagram) (Meta Platforms Inc.(Meta), 2022), but again local data could provide more accuracy. The damage curves is a data set that is provided by the Worldbank and is is dependent on the particular country (Huizinga, De Moel, & Szewczyk, 2017). It already uses Kenya as data so it is not a global estimate.

From these data the most important part is that the water depth data will be obtained from 3Di and uses rainfall data to estimate these water depths as a result of this rainfall. Then the land use cover should be imported to see what types of areas are flooded. The accuracy of the damage calculations will be higher if these 2 data sets are obtained from more local sources.

Next to calculated damages as output, the results of the FIS Tool will also show the following in the chosen scenario region: the gender distribution, the age distribution, the land use distribution, and the affected population (prior to and after the flood).

7.7.3 QGIS

Both the FIS Tool and 3Di require GIS (Geographical Information System) data to produce results. The input data for both software will be generated using QGIS, an open source software in which geospatial information can be created, edited, and visualized (Open Source Geospatial Foundation, 2022). The sections below explain each data source required for the used software.

Digital elevation maps (DEM) are obtained from the Shuttle Radar Topography Mission (SRTM). The latest SRTM product available offers a resolution of 30 x 30 meters. It has managed to provide elevation data on a near global scale. The data set has undergone various void-filling stages to avoid gaps in the elevation rasters (Farr et al., 2007). The DEM data is input into the 3Di software as a basemap for the hydrological model of the software.

Land cover classification to determine the flow friction of the surface. This determines preferential path flows in the 3Di model simulation. The data from the land cover classification is obtained from the world research inistitute (WRI) and divides the catchment into land cover types (World Resources Institute, 2007). Figure 5.6a depicts the land cover classification of the catchment. The friction mechanism follows the Manning formula:

$$Q = \frac{1.49}{n} * A * R^{2/3} * S^{1/2} \tag{7.13}$$

Where: Q = discharge (m^3/s), A = cross sectional area (m^2), R = hydraulic radius (m), S = slope of energy gradient (m/m), and n = Manning's friction coefficient (-). A table with the Manning's friction values per land cover type used in the model can be found in Appendix I.

Catchment Delineation of the Isiolo River Basin to set the boundaries for both the FIS Tool and the 3Di software. A shapefile with the boundaries of the catchment and relevant river streams has been received by SNV, who are currently working on various projects around Isiolo county. The delineation can be found in Appendix D.

Rainfall Interception to simulate local rainfall within the catchment. Unfortunately, with 3Di it is not possible to model local rainfall within a catchment. This means that rainfall can only be input as an equally distributed amount of rainfall throughout the whole model space. To "mimic" the effect of local rainfall, it is possible to submit an interception raster, where the regions where there is no precipitation have an infinite amount rainfall interception. This means only rainfall would fall in areas where there is no interception. The main objective of analyzing this is to see the effects of heavy rainfall upstream of Isiolo Town, which interviews with the local authorities have confirmed is the most common flood mechanism in Isiolo Town.

Soil classification of the Isiolo River Basin. The type of soil cover as depicted in Figure 5.5 shows the distribution throughout the catchment. The soil classification has an influence on the infiltration rate, which determines the amount of rainwater being stored in the soil. Due to the catchment being very clayey, most of the storm water will remain overland. However, high infiltration regions can help infiltrate an excess of overland flow. The data used for the infiltration rates of the catchment come from the IGAD Climate Prediction Application Centre (ICPAC). Table 7.2 shows the respective infiltration rates per soil type (ICPAC, 2015).

Table 7.2: Infiltration rate per soil type (ICPAC, 2015).

Soil type	Infiltration rate (mm/h)
Sandy	25
Loamy	15
Clayey	5
very Clayey	2

Population Isiolo from the Center for Training and Integrated Research in ASAL Development (CETRAD). The CETRAD focusses on management of data in ASAL regions in Kenya for development of such, with a focus on water resources, governance and climate adaptability (Centre for Training and Integrated Research in ASAL Development, 2022). This data can be input in the FIS Tool to estimate the affected population of a certain flood event. As mentioned before, the FIS Tool makes use of a population distribution estimation generated by Account Based Marketing (ABM). This marketing strategy used by social networking company Meta Platforms Inc, formerly known as Facebook Inc, can track the location of its marketed users through various social platforms used on cellular networks across the globe (Meta Platforms Inc.(Meta), 2022).

7.8 SLAMDAM demonstrations

To get an idea of the possible interest of the parties and organisations of interest for the SLAMDAM and to see if the SLAMDAM is well received by both, two demonstrations were given. One of the demonstrations has taken place on October 19, 2022 near Isiolo Town at Kisimani Eco Resort, Maili Saba. For this demonstration, the local community was invited as well to see whether they feel engaged and are receptive to this innovation. Furthermore, the following organizations were present: SNV Nanyuki, WRA ENN basin area Regional Office, WRA Isiolo, WRUA Isiolo, NDMA Isiolo, and Kenya Red Cross.

Figure 7.4: Group picture at the SLAMDAM demonstration, October 19 2022, Maili Saba.

The other demonstration has taken place on October 21, 2022 in Ruiru (Kiambu County), which is located near Nairobi. For this demonstration the national organisations were invited. The following parties came to see the SLAMDAM: SNV Nairobi, WRA Nairobi, WRA Nairobi sub region, WRA Kiambu, WRUA Kiambu, embassy of the Netherlands, Ministry of Water, Sanitation and Irrigation, ActionAid Kenya, and a representative from the Blue Deal Project.

The agenda of both demonstrations and some pictures of the deployment of the SLAMDAM are included in Appendix J. This Appendix also includes a link to a newspaper article in the Nation about the demonstration near Isiolo Town.

Chapter 8

Stakeholders and their challenges

This chapter takes a closer look at the key stakeholders regarding water resources in Kenya. To look at the feasibility of new technologies, it is important to see how this fits within the current plans and policies of both national and local government bodies and other relevant parties. Therefore, first will be described what the legal and institutional framework looks like and the how different stakeholders are involved or related to flood risks. It will then go on to discuss the main stakeholders, their responsibilities, and relationships. Finally, during the project there has been a lot of interaction with various stakeholders by means of interviews, site investigations and, demonstrations, an overview of the main challenges they are experiencing has been conducted. This should help to get a better understanding of the focal points for implementation of new technologies.

8.1 Important laws, policies and plans

To look at the feasibility of new technologies, it is important to consider international trends and the legal and institutional framework. This ensures that implementation of new technologies such as SLAMDAM and the FIS Tool fit within existing laws, policies, and plans. Since it is already clear that global trends such as urbanisation and climate change are visible in Isiolo County and that they are putting more pressure on water resources, international trends will not be discussed further (County Government of Isiolo, 2018). This section is therefore more focused on providing insights into existing laws, policies, and plans regarding water resources and flood risks.

8.1.1 National level

Kenya Vision 2030
One of the key national long-term visions is set out in Kenya Vision 2030. The blueprint was compiled with the help of many stakeholders including international and local people and experts and it launched in 2007. It aims to *"middle income country providing high quality life for all its citizens by the year 2030"* (Government of Kenya, 2007). The vision is divided into three different pillars: economic, social, and political. The environment, water, and sanitation theme falls under the social pillar and is divided into 20 different programs such as Irrigation and Drainage, Water Storage and Harvesting, and Water Resources Management Programme (Government of Kenya, 2007). Important targets outlined in the Kenya Vision 2030 related to the water sector are (Aurecon AMEI Limited, 2020b):

- Water and Sanitation: ensure improved water and sanitation that is available and accessible to all
- Agriculture: increase the area under irrigation to increase agricultural production
- Environment: have a clean, secure and sustainable environment

Big Four Agenda
During the Third Medium Term of the Kenya Vision 2030, former President Uhuru Kenyatta's Big Four Agenda was launched and left its mark on this period (2018-2022) (Government of Kenya, 2007). The critical importance of proper water resources planning and management is evident in relation to Kenya's Big Four Agenda: Food Security, Affordable Housing, Manufacturing and Affordable Health Care for all (Aurecon AMEI Limited, 2020b). In the National Integrated Water Resources Management and Development Plan (2020) the importance of prioritizing agricultural sector productivity because of low water endowment, growing population, and changing climate is described. Increasing productivity is directly linked to the goal of food security. The importance of new technologies and drip irrigation is emphasized here. The Big Four Agenda also recognized the issues around climate change and the pillars are designed accordingly. It identifies the climate actions with as priority one disaster risk management; reduce the risk to communities and infrastructure resulting in climate-related

disasters such as droughts and floods (Aurecon AMEI Limited, 2020a).

Kenya Constitution 2010
As mentioned before in section 2.4, the new constitution brought a lot of changes. The institutional framework for the water sector was restructured and this required changes in the old legislation and institutional structure for water management. The two main implications for the water supply and sanitation sectors (Aurecon AMEI Limited, 2020b):

- The right to clean and safe water in sufficient quantities.
- Division of responsibilities between national and county government. It stipulates the functions and power in the division between who is responsible for storm water management and water and sanitation services.

Water Act 2016
The Water Act 2016 has ensured that water sector in Kenya has been brought in line with the Constitution 2010 and brings in amendments to ensure that water resources are better managed. The Water Act (Act No 12 of 2016) revises the functions and responsibilities of the various water agencies. For instance, mandates are reassessed and rewritten where necessary and responsibilities between national and county government are defined (Aurecon AMEI Limited, 2020b). It defines for example a clear role for the WRA in the regulation of water resources, which provides a potential strengthening in the way that water resource development is regulated. Another important example of decentralized decision-making can be seen in the formation of the WRUA (Aurecon AMEI Limited, 2020b). More is explained about the different roles of water resource institutions later in this chapter.

National Water Master Plan 2030
The NWMP 2030 was launched in 2014 and covers all six basins in Kenya. The NWMP 2030 contains information on water resources, water needs, high-level water allocations, economic assessments of proposed interventions, and implementation programs for each river basin. The aim of the plan is to create a framework to align developments of Kenya's water management with social and economic goals and to incorporate climate change into it (Nippon Koei Co., 2013).

The Kenya National Adaptation Plan (NAP)
With the NAP 2015 to 2030, the government is building on previously made plans. In it, adaptation to climate change is promoted. Goals important to the ENN Basin Plan relate to understanding the urgency of adaptation, building resilience to climate change as an adaptation of development planning and budgeting, and improving resilience of vulnerable residents to climate change and the potential disaster events that follow (Aurecon AMEI Limited, 2020a).

8.1.2 County and local level

County Integrated Development Plan
On a smaller scale, each county in Kenya has its own County Integrated Development Plan after each election are remade. The CIDP 2018-2022 for Isiolo was put together with the County Government of Isiolo and other stakeholders. It describes the plans over this period and covers all sectors. The important purpose of this is to get the plans within the county integrated with each other and should facilitate that developments proceed prosperously (WRA National report). In the CIDP 2018-2022 problems related to water resources like the poor drainage systems and the disastrous results are described. Also, the policy to tackle those problems by strengthening the capacity for climate change, extreme weather, drought, flood, and other disaster are elaborated on (County Government of Isiolo, 2018). Since the CIDP lasts only until 2022, it is necessary to wait for the new plans to be drawn for the county.

Sub-Catchment Management Plan (SCMP)
A SCMP is a tool adopted by the government and implemented through the WRUA to facilitate the implementation of the water resources management at the lowest level. In Isiolo County there is the Isiolo River Basin Integrated Flood Management Plan 2013, which has been referred to earlier. The problem with this is that it is no longer up to date as there has been a new Water Act since 2016. Therefore a new sub-catchment management plan has to be written for the Isiolo River Basin.

Isiolo Urban Economic Development
This document is written as an advisory report for Isiolo County and is part of the SUED programme (Tetra Tech International Development, 2020). It builds on the County's existing CIDP and other plans. The purpose of the plan is to function as a guide for the urban and economic growth strategy in Isiolo. The report emphasises

that for the development of the economy through agriculture and livestock, it is important that infrastructure around water management and solutions to reduce flooding are crucial (Atkins, 2020).

Other relevant plans

Besides the national and local plans mentioned above, there are many initiatives, plans, and policies that can play an important role when it comes to implementation of new technologies against flooding. There are too many to name them all, but some developments that need to be highlighted are the LAPSSET project, development of the international airport, turning Isiolo in one of the Resort City's in Kenya, the Sponge City project and SNV's LISTEN project.

8.2 Stakeholder mapping

In this section the stakeholders that are involved in water resources and flood risks on national and local level will be discussed. Since there are different stakeholders (e.g. private and public parties), they have different responsibilities, visions and needs. Executing changes to an area has an different impact on these parties. By focusing on understanding the characteristics of social networks and considering a range of perspectives, the likelihood of collective action and successful project management is increased (Richards et al., 2004).

First, the institutional framework of water resources will be elaborated on by introducing the different institutions. Also, other relevant stakeholders will also be explained. Their relationships will be shown in a formal chart. This will clarify how to approach different stakeholders and which stakeholders are important to include, for example, in the decision-making process for implementing the SLAMDAM and FIS Tool (De Bruijn & Ten Heuvelhof, 2018).

8.2.1 Institutional Framework

As described before, the Water Act 2016 has ensured that the Kenyan water sector has been aligned with the 2010 Constitution Act. When the new Act was introduced, the Water Resources Management Authority (WRMA) was renamed the Water Resources Authority (WRA). Moreover it came with the acknowledgement of the Water Resources User Association (WRUA) as legal entities for the collaborative management of water resources and conflict resolution. The national government remains responsible for regulating water services and water resources. It also remains in charge of managing national public water works which extend multiple counties are funded from the national government's budget. The Water Act does not assign detailed water management functions to national and county governments, but instead provides for a National Water Resources Strategy. Section 6 of the Act states that regulation of the use and management of water resources is a responsibility of the WRA as an agent of the national government.

Governmental institutions with main focus water resources

Ministry of Water, Sanitation and Irrigation

As sector leader and coordinator takes the responsibility of policy development. The ministry has as mission *'to contribute to national development by promoting and supporting integrated water resource management to enhance water availability and accessibility'* (Ministry of Water, Irrigation and Sanitation, 2021).

National Water Harvesting and Storage Authority (NWHSA)

On behalf of the national government, the NWSA is responsible for undertaking the development and management of national public water works for water resource management and flood control. Moreover, they are responsible for the national government strategic water emergency interventions during droughts and they advise the Cabinet Secretary on matter regarding national public water works and flood control (National Water Harvesting and Storage Authority, n.d.).

Water Resource Authority (WRA)

The WRA has the mandate to protect, conserve, control, and regulate the management and use of water resources by the establishment of a National Water Resource Strategy. Sections 12 and 13 of the Water Act 2016 provide the various function of the WRA. Next to formulating standards, procedures and regulations, planning and issuing of water abstraction permits, setting and collecting permits and water use fees, one of the main functions is to provide information and advice the Cabinet Secretary for policy formulation on National Water Resource Management, water storage, and flood control strategies (Water Resources Authority, 2022a).

Kenya Water Institute (KEWI)

The KEWI is an institution that is mandated by the KEWI Act 2001 to provide training, research, and consultancy services in the wider water sector. The Act also stipulates that the KEWI should provide a forum for effective cooperation between the public and private sectors and other stakeholders for the development of the water and sanitation sectors. It is a semi-autonomous government agency and is therefore also responsible for generating income on its own (Kenya Water Institute, 2022) (Aurecon AMEI Limited, 2020b).

Water Tribunal

They used to be called the Water Appeals Board. Nowadays it includes more members and their main function is to resolute disputes (Aurecon AMEI Limited, 2020b).

Water Sector Trust Fund (WSTF)

Under the Water Act 2002 is was known as the Water Services Trust Fund. It mandates has been expanded to provide conditional and unconditional grants to counties to assist in financing development towards the underserved and marginalized areas (Water Sector Trust Fund, 2022).

Water Services Regulatory Board (WASREB)

WASREB is the regulatory state corporation with as main objectives to guarantee the right of consumers in the provision of water services. This is crucial to protect users from being exploited and it sets the minimal national standards. The WASREB has the mandates to set, monitor, and review rules and regulations to ensure water services provision is affordable, efficient and effective (Water Services Regulatory Board, 2020) (Aurecon AMEI Limited, 2020b).

Basin Water Resources Committee (BWRC)

The BWRC will replace the Catchment Advisory Committees (CAAC's). The BWRC is involved in catchment management activities on behalf of the WRA at regional level (Water Resources Authority, 2022b). The BWRC plays a more managerial role than the purely advisory role of the CAACs (Aurecon AMEI Limited, 2020b). This new committee has the same regional responsibilities as the CAAC's which is to manage the catchments and to facilitate establishment of WRUA's. A representative of the county government will take a seat in the BWRC in which it geographical jurisdiction falls. ENN BWRC has not been established and is not operational (Aurecon AMEI Limited, 2020a). So they do not exist, but their composition is enumerated in the Water Resources Regulation 2021, which is basin-based and includes all provinces within the basin (E. Diego, e-mail, 12 September 2022).

Water Works Development Agencies (WWDA's)

The WWDA's replaced the old Water Service Boards. In the Water Act 2016 the Cabinet Secretary has been given the power to establish as many Water Works Developments Agencies as necessary to manage, maintain, and develop national public water works (Aurecon AMEI Limited, 2020b). On the other hand, the county public works falls under the responsibility of the respective county and the Water Act 2016 provides for transferring national public works to the county government, a joint committee, or authority of the county government if the water works geographically completely falls within the counties jurisdiction. To successfully execute their mandate, the Agency will develop water supply and sewerage infrastructure and activity engage stakeholders (Northern Water Works Development Agency, 2020).

Water Resources User Association (WRUA's)

The Water Act 2016 provides for establishment of WRUAs, which are community-based associations for collective management of water resources and resolution of conflicts concerning the use of water resources. The WRA and WRUA work in close cooperation together (Aurecon AMEI Limited, 2020b). The WRUA have been instrumental in the implementation of the Sub-Catchment Management Plans (SCMP's) which has resulted in improved catchment conditions in areas where WRUA's exist. WRUA are on a voluntary basis and as can be seen in Figure 8.1 not all the WRUA's have been officially formed yet.

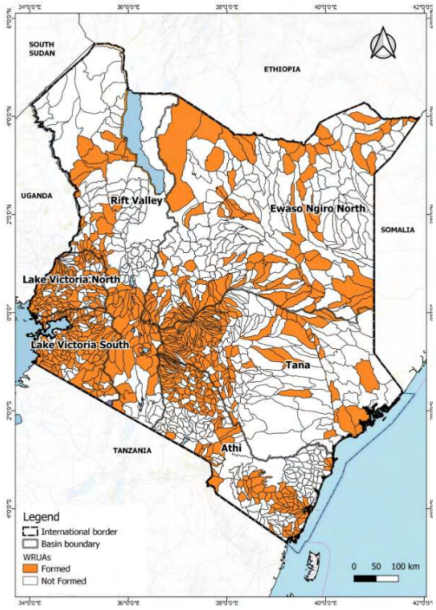


Figure 8.1: WRUA status (Aurecon AMEI Limited, 2020b)

The Water Resource Users Association Development Cycle (WDC) is designed to provide technical and financial support for community based activities in water resource management (The Water Services Trust Fund and Water Resources Management Authority, 2009). In 2017, WRA published the newly developed Water Resource Users Associations Capacity Assessment Tool, as there has been an growing demand to assess the capacity of WRUAs to identify any gaps in the governance and implementation of their mandate. The tool will support WRUAs to improve their performance in management of water resources at sub-catchment level (Water Resources Authority, 2009).

Water Service Providers (WSP's)

Together with the county government they provide water and sanitation services in county. Operations must be in accordance with a Service Level Agreement wherefore the WSP's must apply for new licenses to the WASREB (Aurecon AMEI Limited, 2020b) (WASREB, 2020).

The overall water sector institutional framework can be seen in Figure 8.2.

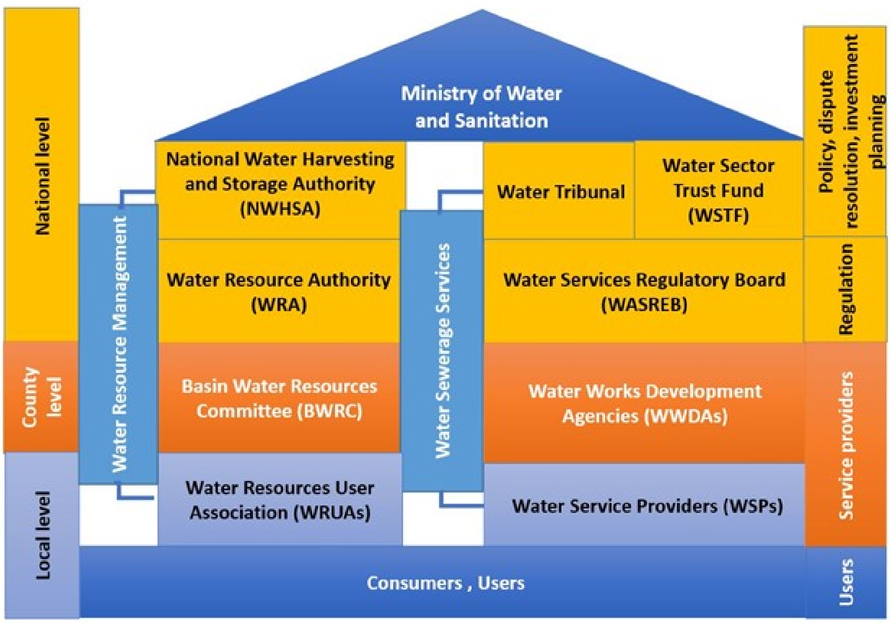


Figure 8.2: Water sector institutional framework (Ministry of Water, Sanitation and Irrigation, 2019)

Other governmental stakeholders
Next to the institutions that mainly focus on the management of water resources, there are some other key governmental parties that play a role in flood risk mitigation and basin planning. Apart from some ministries that have important functions, there are also some entities under these ministries that are important to include. A description of these parties is given in the next part as well as their mandates and main interests.

Ministry of Environment and Forestry
The Ministry of Environment and Forestry has the mandates, among others, to undertake National Environment Policy and Management, Restoration of strategic water towers, Protection and conservation of Natural environment, Kenya Meteorological department, Conservation and protection of wetlands, and climate change affairs. The Ministry is committed to laws and regulations to promote environmental sustainability and forest resources while at the same time thinking to counter the effects of climate change. Thus one of its goals is to engage in climate change resilience and improve low-emission developments in all economic sectors. Adding to this, the ministry wants to improve the generation and sharing of weather and climate information for early warning, planning decision-making (Ministry of Environment and Forestry, 2013).

Ministry of Agriculture, Livestock, Fisheries and Co-operatives
This ministry is committed to the agricultural sector, livestock, and fisheries. The ministry wants to ensure that they promote agricultural developments and improve the productivity of the agricultural sector. In addition, one of its goals is to ensure national food security. So the ministry has an interest in projects related to irrigation and protection of crops (Ministry of Agriculture, Livestock and Fisheries, n.d.).

Ministry of Devolution and ASALs
The Ministry of Devolution and ASALs consists of two State Departmets: namely Devolution and ASALs. They were both part of the defunct Ministry of Devolution and Planning, but since Executive order No. 1 of June 2018 (Revised) it has its own mandates. They are responsible for supporting the county governments through policy formulation and intergovernmental relation. Moreover, it manages the shared responsibility of disaster risk management between national and county government (Ministry of Devolution and ASAL, 2019).

Kenya Meteorological Department (KMD)
KMD has the mandate to provide early weather and climate information. In doing so, it aims to ensure safety, protect property, and preserve natural environment. One of their core functions is to improve knowledge and techniques to provide better forecasts and thereby be able to issue timely warnings and alerts in case of severe weather or extreme climate events (Kenya Meteorological Department, 2021).

Kenya Water Towers Agency (KWTA)
KWTA is mandated to oversee and coordinate the protection, rehabilitation, conservation, and sustainable management of water towers in Kenya. The agency falls under the Ministry of Environment and Forestry. The water towers are important for things like irrigation and agriculture. The agency says water towers in Kenya are under pressure from human and natural threats such as drought, floods, and (il)legal settlements (Water Towers Kenya, 2021). KWTA is also about coordinating and monitoring restoration of forest areas, wetlands and biodiversity hotspots (Aurecon AMEI Limited, 2020b).

National Environment Management Authority (NEMA)
The NEMA is a national organisation established in 2002 from the merger of three governmental departments. It monitors, assesses, and coordinates environmental activities and promotes environmental considerations in developments (Aurecon AMEI Limited, 2020b). In doing so, it is one of the leading national bodies in implementing environmental policies across all sectors. Besides being a regulatory body, it also carries out its own projects. These may include building resilience to climate change and protecting vulnerable areas. They thus cheer low-emission and climate-resilient projects that help achieve Kenya Vision 2030 goals (Green Climate Fund, n.d.).

National Drought Management Authority (NDMA)
Being founded in 2018, it is a relatively new organization. The NDMA is a public body that established by the National Drought Management Authority Act (2016) and the agency falls under the Ministry of Planning and Devolution (which later became the Ministry of Devolution and ASALs and the Planning department is moved to the National Treasury). It gives the NDMA the mandate *'to exercise overall coordination over all matters relating to drought management including implementation of policies and programs relating to drought management'* (National Drought Management Authority, 2022). There are several offices in 23 ASAL counties, one of them being Isiolo. The NDMA develops drought plans and coordinates emergency response interventions. Drought monitoring, drought early warning and severity assessment has been conducted with inputs from KMD, WRA Offices and related Ministries (Aurecon AMEI Limited, 2020a) (Aurecon AMEI Limited, 2020b).

National Disaster Operation Centre (NDOC)
The NDOC was founded in 1998 to act as the focal point for coordinating disaster response operations in Kenya. The public body has the mandate to monitor, coordinate, and mobilize national resources to respond to disaster incidents (United Nation, n.d.). The agency works together with actors like the police and the Kenya Red Cross. Besides response, the NDOC also plays a preparatory role by managing the national disaster database (Aurecon AMEI Limited, 2020a).

National Disaster Management Unit (NDMU)
The NDMU was established in 2013 as an effective and competent disaster management unit together with Standard Operating Procedures (SOPs) based on best practices. In collaboration with other stakeholders they formulated the National Emergency Disaster Plan and SOPs. The National plan and SOPs are set out in the medium-term plans phase 2 of Kenya Vision 2030, which addresses safety, security, and protection of Kenyan assets from hazards and disasters (Aurecon AMEI Limited, 2020a). NDMU is an agency that falls under the Ministry of Interior and Coordination of National Government. The SOPs within the plan provides a strategic, operational, and tactical guide for National Disaster Management Unit, government agencies, and private partners during emergency incidents in the country (National Disaster Management Unit, 2020).

National Disaster Management Authoriy
In 2021 the Disaster Risk Management Bill was presented to parliament. The mandates of NDMA, NDOC, and NDMU clearly overlap in various ways. Therefore the idea was launched to bring them together under one agency as a new "Disaster Risk Management Authority." (Aurecon AMEI Limited, 2020b). The Bill is for an act to establish the National Disaster Risk Management Authority and County Disaster Risk Management Committees; to provide a legal framework for the coordination of disaster risk management activities and for connected purposes.

Other relevant non-governmental parties
There are also non-governmental parties that play an important role in Kenya and in relation to this project. These include NGOs, financial institutions, the private sector, foreign government bodies or agencies, and the Isiolo society. A brief list of these types of parties with some examples is given below:

- NGOs
  - Kenya Red Cross
  - ActionAid
  - UNEP
  - SNV
  - WWF
  - World Waternet
- Financial institutions
  - World Bank
  - African Development Bank
- Private sector
  - Nelen & Schuurmans
  - Zephyr Consulting
  - TetraTech International Development
- Foreign government bodies / agencies
  - Embassy of the Netherlands
  - JICA
- Isiolo Society
  - Residents
  - Farmers and local businesses
  - Isiolo International Airport

8.2.2 Formal chart

In the formal chart the stakeholders are shown that are relevant to consider for this project. A formal chart is often used in policy analysis for multi-actor problems (Hermans, Kwakkel, Thissen, Koppenjan, & Bots, 2010). The chart shows the different relations between the stakeholders involved in this project. It is based on the stakeholders that have been described in the previous sections and shows the relations between different entities that have a possible influence on the potential implementation of flood risk mitigation measures. The type of relations can be derived from the chart, see Figure 8.3.

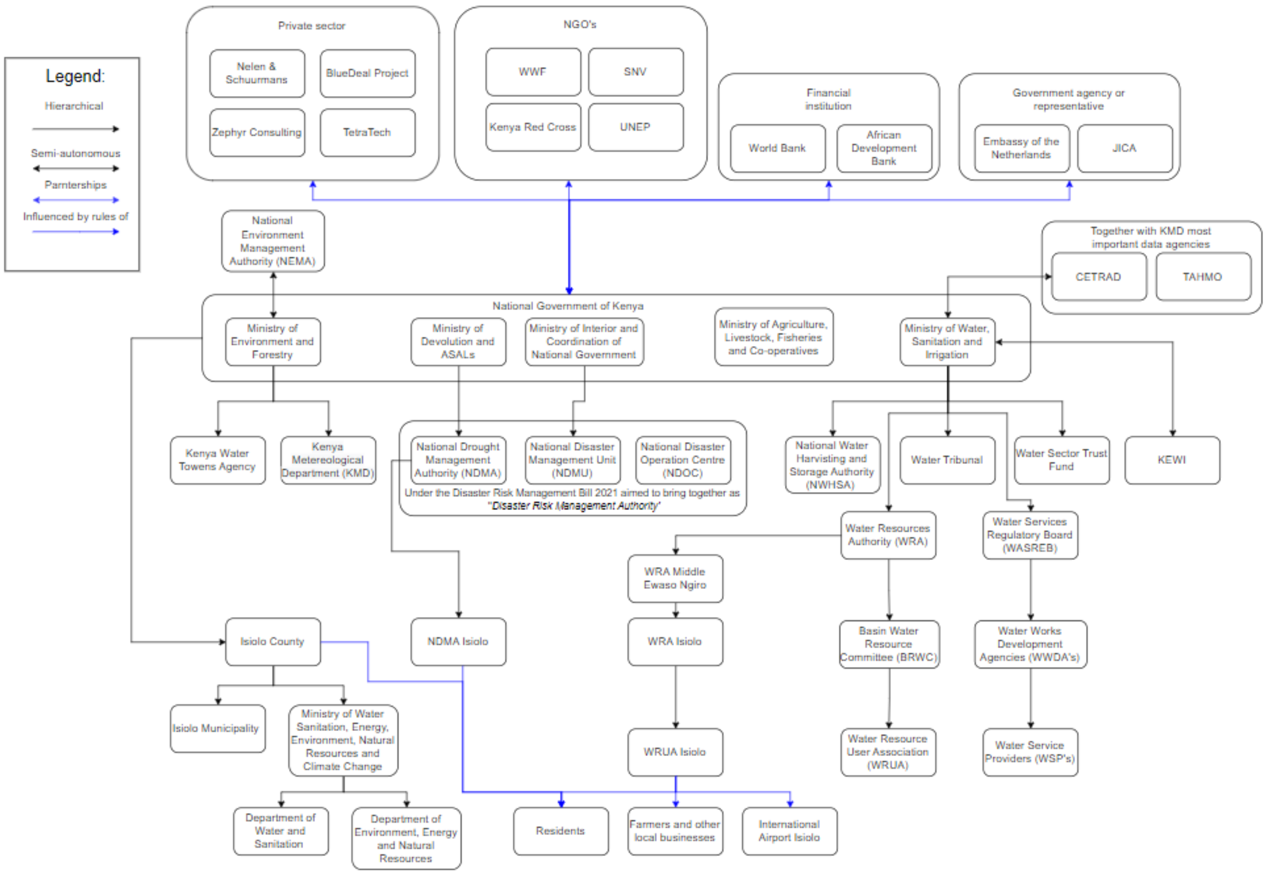


Figure 8.3: Formal chart of stakeholders and their relations

It should be noted that the figure only shows a partnership relationship between the national government of Kenya and private sectors, NGOs, financial institutions, and other foreign government organisations. To keep the figure clear, partnerships with lower-level Kenyan government bodies have been left out. However, this does not necessarily mean that such relationships do not exist. However, it is important to realise that if a technology were to be used at the local level, for example in the Isiolo River Basin, it would still require permission from the national Ministry of Water, Irrigation and Sanitation.

8.3 Challenges

8.3.1 Overview stakeholder interaction during project

During the project, multiple interviews, correspondence with several stakeholders, meetings, site investigations, and demonstrations were held. These events were important for data collections and gathering more information about flood risks. In addition, during these interactions stakeholders were asked about their experiences and the biggest challenges they experience now or have experienced in the past related to project management. This was particularly focused on the challenges regarding flood risk, but can also apply to other challenges from other types of projects and people were free to share their experiences. An overview of all the interviews, site investigations, and demonstrations can be seen in Table 8.1.

Table 8.1: Overview of interactions with stakeholders

Date	Type of interaction	Organisation	Name(s)
6-9-2022	Interview	Zephyr Consultin	Lilian Kalela
7-9-2022	Interview	WRA Nairobi	Pauline Wanjiku Nyamu Betty Barassa Joash Nyakora
9-9-2022	Interview	SNV Nairobi	Jeen Kootstra
15-9-2022	Interview	Embassy of the Netherlands	Pim van der Male Laura Ammerlaan
22-9-2022	Interview	NDMA Nairobi	Clinton Ouma
29-9-2022	Webinar	WRA Nairobi WRA ENN Basin Area Regional Office Embassy of the Netherlands	Pauline Wanjiku Nyamu Betty Barassa John Munyoa Pim van der Male Laura Ammerlaan
29-9-2022	Meeting	WRA Kiambu WRA Nairobi	Noel Ndeti & two other employees Pauline Wanjiku Nyamu
3-10-2022	Meeting	SNV Nanyuki	James Mwangi
3-10-2022	Interview	WRA ENN Basin Area Regional Office	John Munyoa Mugambi Muthinja
4-10-2022	Interview	WRA Isiolo	Agathe Warutere Mercy Mbaya David Kisela
4-10-2022	Interview	NDMA Isiolo	Omar Abduhalli Abdi
4-10-2022	Site investigation	Local community in Isiolo	Names unknown
6-10-2022	Interview & Site investigation	WRUA Isiolo	David Mwiti
			Helen Murungi Casheli Mutungi Francise Mwangi John Taipi Anthony Chepriko Joseph Kuwam John Kithinji Kenneth Mwemda Martin Mugambi
7-10-2022	Meeting	CETRAD	Name unknown
19-10-2022	Demonstration Isiolo	WRUA Isiolo Kenya Red Cross WRA ENN Basin Area Regional Office WRA Isiolo NDMA Isiolo SNV Nanyuki	34 persons in total present
21-10-2022	Demonstration Nairobi	WRUA Kiambu WRA Kiambu WRA Nairobi WRA Basin Area Regional Office Ministry of Water, Irritation and Sanition ActionAid Embassy of the Netherlands Blue Deal Programme SNV Nairobi	31 persons in total present
27-10-2022	Webinar	WRA Nairobi ActionAid Ministry of Water, Irritation and Sanition ICPAC SNV Nairobi WRA Isiolo World Waternet	Pauline Wanjiku Nyamu Cynthia Wechabe Carey Owiti Khalid Hassaballah Steven Gichuki Mercy Mbaya Simon Muturi

Next, all the mini-stories and experiences were compiled. Although stakeholders have different interests and demands, they gave examples of problems and challenges of project management that are somewhat related to each other. Therefore several categories were drawn up to which the stories were linked. This method is called open coding, axial coding, and selective coding and it is used in the grounded theory method of analyzing qualitative data. The research of Ninan, Mahalingam, and Clegg (2019) on external stakeholder management has been used as an example. In this research practices from stakeholders during megaprojects are linked to a certain strategy category. In this report, the same kind of table has been created with can be seen in Table 8.2. The table shows the amount of mini-stories, the source and its type, the mini-story itself, the corresponding category, and the solution. It should be noted that the mini-stories are not exact quotes, but based on notes from the interactions with all the stakeholders. Therefore, the source may have used different words. The solution given in the last column was either discussed during the interview as possible solution or it is based from other stakeholders' stories, own practices, and advice.

Table 8.2: Overview mini-stories and solutions

No	Type of Source	Name / Organization	Mini story	Category	Solution
1	Interview	Zephyr Consulting	To get the SLAMDAM into Kenya for demonstrations, a tax exemption is required.	Financial / funding	Support from SNV, Embassy of the Kingdom of the Netherlands or other party with governmental status
2	Interview	Zephyr Consulting	Experiences from previous projects in Burundi and Nigeria have shown that to deploy SLAMDAM successfully, the local community must be open to new technologies.	Community Engagement	The local community should be involved in an early stage so that they themselves see the benefits and feel involved.
3	Interview	Zephyr Consulting	Unfortunately, mismanagement of money continues to take place in the implementation and procurement of projects in Kenya.	Corruption	Avoid corruption whenever possible and report to agencies as soon as occurs.
4	Interview	WRA Nairobi	There is no government agency whose main task is flood protection.	Institutional	It should be clear who is responsible for dealing with floods, perhaps a special agency or department should be set up for this purpose.
5	Mail correspondence	WRA Nairobi	Membership of WRUA is on a voluntary basis.	Institutional	There has been developed a framework of engagement of all the WRUAs through the WRUA Development Cycle (WDC).
6	Mail correspondence	WRA Nairobi	Currently there are 730 WRUAs with an optimum of 1237 delineated areas for WRUAs in Kenya	Institutional	In 2017, WRA published the newly developed Water Resource Users Associations Capacity Assessment Tool, as there has been an growing demand to assess the capacity of WRUAs to identify any gaps in the governance and implementation of their mandate.
7	Mail correspondence	WRA Nairobi	The BWRC have not been formed yet, but their composition is enumerated in the Water Resources Regulation 2021 that is Basin Area based encompassing all counties within the Basin Areas.	Institutional	There is more time required to set up those institutions.
8	Mail correspondence	WRA Nairobi	Is financing of water resources activities for the WRUAs there is preference on water supply	Financial / funding	Stress the importance of flood risk reduction and equitably weigh the various interests.
9	Interview	SNV	There is fragmentation of government agencies where it is sometimes unclear who is responsible for what. Sometimes there is overlap in this, sometimes not, and for WRUAs it can be difficult to deal with this when dealing with multiple counties.	Institutional	When writing policy for a sub-catchment, division of responsibilites should be clear. Also, WRUAs can make use of WDC and the WRUA Capacity Assessment Tool.
10	Interview	SNV	Because corruption is still prevalent in Kenya, it is difficult to bring in (foreign) funding.	Financial / funding	Strict conditions are set before money is spent and outsourcing is carefully tracked. Partners report monthly where money is going, what it has been spent on. No lump sum amounts are ever committed.
11	Interview	SNV	It is sometimes unclear what money is used for or people try to make abuse of the situation for own purposes. For example, when people attend a workshop, they fill in a name for several people that they attended so that they themselves get more money.	Corruption	All expenses and delcarations are accurately tracked. For example, kilometres driven, how many office spaces and employees are needed, etc. Make estimates in advance. In example of double attendance at a workshop, all signatures are additionally checked afterwards.

No	Type of Source	Name / Organization	Mini story	Category	Solution
12	Interview	Netherlands Embassy	Experience shows that many temporary solutions are devised because it is unclear who is responsible for what.	Institutional	When implementing policies, the effects of a measure or intervention should be carefully considered; are they realistic and sustainable solutions?
13	Interview	Netherlands Embassy	Counties write their own policies, but water does not abide by those boundaries. Sometimes counties' policies do not align with each other.	Institutional	Takes time to align policies, support from parties such as SNV and Embassy could help with this.
14	Interview	Netherlands Embassy	It can be difficult to engage individuals.	Community Engagement	For this reason, social representation such as WRUAs and wards have found to be useful.
15	Interview	Netherlands Embassy	A new technological solution may work perfectly, but may not fit in certain context or place. Example that counties or farmers are quick to accept anything, because for them it's easy to accept the "free money" and support coming their way. There needs to be a good understanding of the actual impact and whether the solution matches the demand/problem.	Effectiveness of project	Dialogue with local parties very important and looking at sustainability of project.
16	Interview	SNV	County governments and the WRA are new since the Constitution 2010 and Water Act 2016, so many new policies have to be written.	Institutional	Parties like SNV help in policy formulation and they think about integration of plans and activities.
17	Own experience	Student team TU Delft	Many parties say data is available, but it is almost impossible to get suitable data.	Data collection	It helps to submit signed letter with official application or physically visit offices; take for instance CETRAD Nanyuki where student went along with WRA employee and received same-day dataset.
18	Interview	WRA Isiolo	As for water resource management, not all people upstream want to retain water for the people in the city downstream. Not everyone has a lot of land and then find it unacceptable that specifically their land should be used.	Community Engagement	Actively engage local community and use demonstration so people experience the benefits in real life.
19	Interview	WRA Isiolo	If the land is privately owned, why would they want to accept SLAMDAM? Some people are reluctant and do not see the benefits for themselves; new technology cannot then be successfully implemented.	Community Engagement	Conduct clear policies for flood risk measures that cross land ownership boundaries and involve local people at an early stage so that they adopt an accepting attitude.
20	Interview	WRA Isiolo	There are a lot of offices geographically seen to be served.	Effectiveness of project	Create a clearer workflow schedule so meetings and agreements can be shared faster and more transparent
21	Interview	WRA Isiolo	There are many projects, the allocation of financial resources is difficult in such a large area. Money can only be spent once, and if the first project turns out to be more expensive, another project cannot go forward.	Financial / funding	Trying to budget as best as possible and build in buffers.
22	Interview	WRA Isiolo	Floods don't have boundaries, cooperation with different counties and offices is required, which can be challenging as they could differ in opinions.	Institutional	Close coorperation between counties and trying to get integrated management plans.
23	Interview	WRA Isiolo	Sometimes data collection is done manually (which is hard to read) and on a voluntary basis. Hard to check if people are passing the right numbers or just making something up.	Data collection	Use money or some other type of reward instead of voluntariness. People become more responsible and try harder to take correct measurements -> create incentive

No	Type of Source	Name / Organization	Mini story	Category	Solution
24	Interview	WRA Isiolo	There is a lot of vandalism of early warning systems. People steal it for steel.	Data collection	Create local awareness to not demolish measurement equipment since it's in their own best to collect the data.
25	Interview	WRA Isiolo	In recent years, there have been few floods, so people need to be actively reminded again of the importance of taking action against the effects of climate change.	Community Engagement	Create local awareness, potentially through WRUA
26	Interview	WRA Nanyuki	Not enough data is available or data is outdated. If there are gaps in the data, they use gut feeling.	Data collection	Restore early warning systems or find other ways to get better data.
27	Interview	WRA Nanyuki	There is a land use problem: land ownership is increasingly (sub)divided, as pieces of land are transferred among e.g. family, it will only get further fragmented. Water flows over land from multiple owners and everyone uses their land as they wish and its quesionable if everyone is willing to accept new technologies.	Community Engagement	Use demonstration to actively convice people of the new technology
28	During site investigation	WRA Nanyuki	Interventions upstream affect people downstream. Water use and flooding interventions must be designed so that it does not negatively affect downstream.	Institutional	Clear and integrated policy is needed
29	Site visit	WRUA Isiolo	WRUA is voluntary and therefore people should feel some sense of responsibility to the community or affection with issues surrounding water resources.	Institutional	Actively approach people and locals should be convinced of the importance.
30	Own experience	Student team TU Delft	People like to see financial compensation for "inconvenience" or 'trouble" that they experience. Without prepayment, nothing happens.	Corruption	Unfortunately, it turned out that to get something done, you can't always make your way around it. Could help to make firm agreements about work to be done and stand your ground.
31	During demonstration	ActionAid	Early warning system is not strong enough in Kenya. Government had not antipicated enough on the drought and floods, and early warning systems are really important for prepareness for disasters in food supply, evacuation etc.	Data collection	In addition to stakeholders such as the government, NGOs and foreign partners should provide support in developing new systems and strengthening measurement machinery and technologies.

The mini-stories were used to create Figure 8.4. This figure is inspired on the research of (Ninan & Sergeeva, 2022) on mobilizing megaprojects narratives for external stakeholders. This examines how narratives can be mobilised through narrative tools and processes using a case study in United Kingdom. The open codes leading to an axial code, are eventually lined to an aggregate category. The same structure has been used in this report. The mini-stories act as open codes that are then linked to an category. Finally, all categories lead to points of interest that are used in the discussion and recommendations of this report. When a company like Nelen & Schuurmans or Zephyr Consulting wants to enter the Kenyan market and implement their new technologies in the Isiolo River Basin or more generally in Kenya, these aspects need to be taken into account. It is good to consider this in advance to avoid that problems occur later during project implementation.

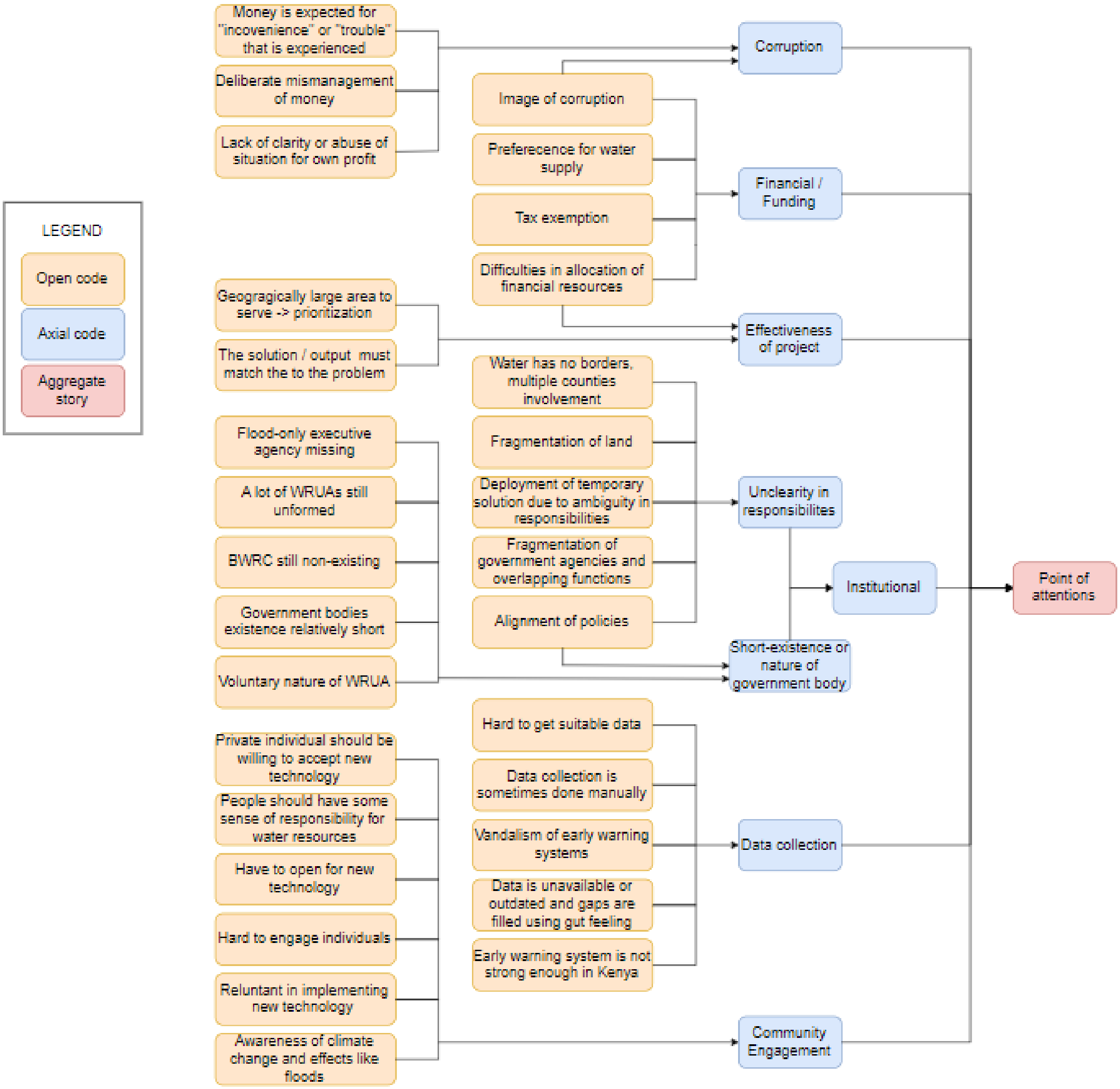


Figure 8.4: Coupling of mini-stories to categories

As can be seen in Figure 8.4 the mini-stories are categorised in challenges concerning corruption, financing / funding, effectiveness of project, lack of clarity in responsibilities, short existence or nature of government body, data collection, and community engagement. Lack of clarity in responsibilities and short existence or nature of government body is combined as an institutional issue. All the categories together lead to points of attention that are being used in chapter 12 Discussion and Recommendations.

Chapter 9

Flood risk and flood maps Isiolo River Basin

Chapter 5 has already provided an indication about flood risk for Isiolo Town and Isiolo County, but this chapter will discuss the flood risk in the Isiolo River Basin in specific. The basin has been visited for this study and the risk has been assessed for the basin as well as for Isiolo Town in specific, because the majority of the population in the basin is housed in Isiolo Town. Flood maps made with 3Di show the water level as a result of certain rainfall events, which are first calculated based on extreme value analysis. These flood maps indicate where the flood risk is high within the basin. With this knowledge, specific locations for mitigation measures can be recommended. The possible implementation of SLAMDAM will be discussed in the next chapter. Afterwards, chapter 11 will evaluate the SLAMDAM in comparison with other flood risk mitigation measures.

9.1 Flood risk assessment

First, this section will assess the risk in the Isiolo River Basin, where mostly natural conditions form a hazard. Isiolo Town will be discussed separately as well, since this urban area is accompanied by extra hazards. Besides, Isiolo Town includes the vast majority of the population of the whole river basin. Figure 5.11 already showed this.

9.1.1 Hazards Isiolo River Basin

The Isiolo River Basin deals with a high geographical gradient because it is located on the foot of Mount Kenya. The gradient of the Isiolo River is visualised in the following Figure:

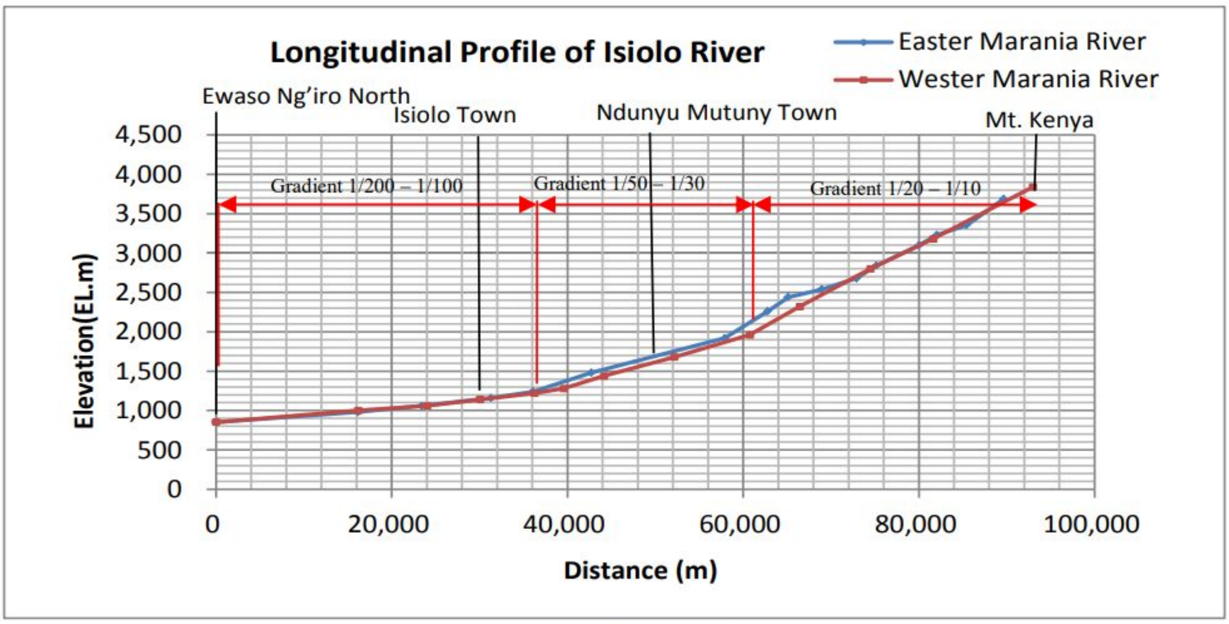


Figure 9.1: Longitudinal profile of Isiolo River (Republic of Kenya, 2013)

This generally steep topographic slope of the Isiolo River Basin results in a short flood arrival time. Flooding occurs fast after the start of rainfall and the flooding peak discharge is high (Republic of Kenya, 2013).

The entire basin experiences also an increased flood risk because most of the basin is arid zone and normally the streamflow is small. Also, the rain events can be very local. The result is aggradation of the river bed by runoff of the soil and a short river width. Next to this, the whole basin is prone to deforestation. This leads to more soil erosion and soil runoff. Mainly farming land and transportation infrastructure suffers from this bank erosion type of flooding (Republic of Kenya, 2013).

The middle river basin deals with several other specific natural conditions and hazards. The geographical gradient is higher, resulting in an even higher flow velocity and unstable water course due to the sharp inclination of the river. Also, the soil is sandy (as visualized in Figure 5.5), which is vulnerable to erode. Besides, there is an accumulation of runoff in the middle river basin, because the clayey soil in the upstream near Mount Kenya leads to less infiltration of rainwater there and more runoff to downstream, so to the middle river basin (Republic of Kenya, 2013).

The upstream part of the basin also deals with specific natural conditions increasing the risk: the very high gradient of the river bed (1/10) results in very high water velocity due to the extremely sharp inclination. Furthermore, the region consists of clayey soil but there is also presence of volcanic sediment. Soil with mainly volcanic sediment is easy to break so the surface soil layer is likely to be highly effective erosional agents (Republic of Kenya, 2013).

With regard to Isiolo Town, this urban area is also prone to natural conditions that can form a hazard for inundation. The steep gradient of the river bed results here as well in a high flow velocity of water and a short flood arrival time. Besides, the geographical conditions form a hazard in Isiolo Town, As discussed in section 5.3.1 and as visualized in Figure 5.5, there is very clayey soil in Isiolo Town which results in barely seepage and more in runoff. Other contributing factors are the semi-arid zones where the area is located and the shrub zone vegetation in the urban area of Isiolo Town. As a result, interception of rainfall and water retention function cannot be very effective (Republic of Kenya, 2013).

Lastly, an important hazard which applies for the whole basin is the effect of climate change. The basin is prone to extreme weather events, which already often result in flooding, as the daily rainfall can be very high (Republic of Kenya, 2013). As discussed in section 4.3, climate change will increase the magnitude of extreme rainfall events. Besides, this section has discussed that climate change predictions has shown that the ENN basin is most prone to climate change with regard to percentage increase in mean annual precipitation. The Isiolo River Basin located in this ENN basin is therefore to be seen vulnerable to climate change with an increase in magnitude of (extreme) rainfall events and as a result an increase in flooding.

9.1.2 Additional hazards Isiolo Town

Besides the hazards in Isiolo Town as discussed above, the town is also prone to additional specific hazards. These hazards has resulted that over the past three decades, flood risk has increased significantly (Atkins, 2020).

The risk of flooding in Isiolo Town is specifically high due to the fact that it is located at the bottom of a valley and is affected by overland runoff from surrounding land. Since Isiolo Town is located at the receiving end of a watershed, the water is generated not only within its own city, but is also originating from upstream areas, resulting in an accumulation of runoff (MetaMeta, 2022). So the flooding does not necessarily need to be the result of local rainfall, moreover it is often the result of heavy rainfall upstream. The rainwater that drains to the surrounding hillsides converges in Isiolo Town with a low arrival time because of the steep slopes. This accumulation of rainwater results in a higher chance of flooding. It can cause flooding of depths up to 500 mm (Atkins, 2020). Interviews conducted with the WRUA confirmed occurring water depths of half a meter as well (WRUA, personal communication, October 6 2022).

Isiolo deals with river-induced flood as a result of this rainfall. If the flow capacity of a river is lower than the flood peak, inundation will occur. The flow capacity of the Merire River, which runs through the town, is examined. The Merire River is visited during the site visit at a location just upstream of the town. The pictures of the river from both sides of the river can be seen in the Figure 9.2.

The width and height of the river must be estimated to calculate the cross-sectional area and the flow capacity of the river. The river on both sides of the bridge differ in apparent width. It is therefore hard to determine the width solely based on the site visit, so the river has also been followed more into town via Google Maps. A picture of Google Maps is also visible in the figure below:

(a) Picture of the Merire River just upstream of Isiolo Town made during the site investigation, looking upstream (upper picture) and downstream (lower picture) of the bridge.

(b) Merire River in Isiolo Town via Google Maps Street View (Google Maps, 2022).

Figure 9.2: Pictures of the Merire River which runs through Isiolo Town

These observations have resulted in an estimation of a width of 5 meters for the Merire River. The height is considered to be 0.5 m. The cross-section is considered to be rectangular for this calculation, so A = width x height, which is 5 m x 0.5 m = 2.5 m^2. Then, the Equation addressed in 7.2 can be used to determine the flow capacity of this river.

Because of the assumed dimension of the river, the river is considered to be a small watercourse. Since the soil within Isiolo Town is very clayey which is a heavy soil, the Strickler Coefficient can be found in Table 7.1 by considering a small waterway with heavy soils. The Stricker Coefficient is found to be 25 $m^{1/3}/s$ for both summer and winter for the Merire River. Furthermore, the wetted perimeter P Is equal to the width + 2 x height for a rectangular shaped river. For this river, P is therefore $5 + 0.5 + 0.5 = 6m$. The hydraulic radius R is therefore $A/P = 2.5/6 = 0.42m$. With these values, the flow capacity of the river channel is:

$$25m^{1/3}/s * 2.5m^2 * 0.42^{2/3} * (\frac{1}{100})^{1/2} = 3.5m^3/s \tag{9.1}$$

The JICA team has performed calculations on the peak flood discharge, by using the calculated rainfall for different return periods based on rainfall data from the Timau Marania Station. Since no more recent data has become available as discussed in section 7.6.2, the same data set is used for this report. And as will become clear in section 9.3.2 of this chapter, the calculated daily rainfall for different return periods by using Annual Maxima in this report is almost similar to the obtained values of the JICA. Since the calculation of the peak discharge is based on these almost similar daily rainfall values, the calculation of the peak discharge will not be performed again, but the outcome from the JICA is used to briefly compare the peak discharge with the calculated flow capacity of the Merire River. The peak discharge for T=5, with rainfall of 82 mm/day, is found to be 71 m^3/s (Republic of Kenya, 2013). This calculation is done with the Rational Formula as provided in Equation 7.1. And although not all flood discharge will run through into the town area, the flow capacity of 3.5 m^3/s is still far beyond this flood discharge with a return period of 5 years. This lack of capacity of the Merire River in Isiolo Town results in frequent inundation. Top of that, possible solutions like widening of the river are hampered since there are houses illegally built in the riparian land.

Besides the natural river which lacks capacity, the urban drainage is also an issue (Nippon Koei Co., 2013). The drainage system is inadequate for the peak flows experienced in Isiolo Town (Atkins, 2020). During the site visit in Isiolo Town, the drainage canals along the main streets were observed with regard to size. By following the same steps as for the Merire River, the flow capacity in the largest observed drainage canal along the A2 which runs through the town is observed to be around 2 meters and the height is 0.8 meters. The picture of the drainage canal can be found in Appendix K.

The canal is made of concrete. The Strickler coefficient is therefore 70 m^3/s (O.A.C Hoes and N.C. van de Giesen, 2022). The cross-section is again considered to be rectangular, so the area is A = 2 x 0.8 = 1.6 m^2. The wetted perimeter P is equal to the width + 2 x height for a rectangular shape, so P is therefore $2 + 0.8 + 0.8 = 3.6m$. This results in a hydraulic radius R of $A/P = 1.6/3.6 = 0.44m$. With these values, the flow capacity of the river channel is:

$$70m^{1/3}/s * 1.6m^2 * 0.44^{2/3} * (\frac{1}{100})^{1/2} = 6.5m^3/s \quad (9.2)$$

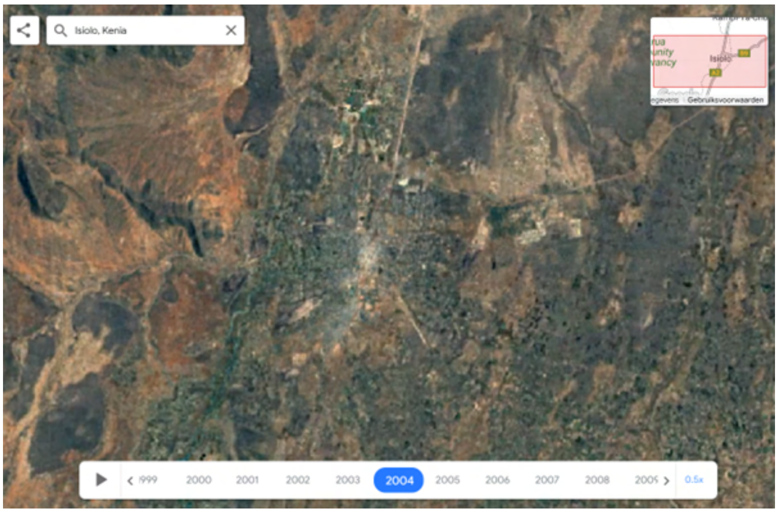
Again, this flow capacity is insufficient for the flood peak discharges.

Other drainage related issues have also been observed. There are many blocked culverts in Isiolo Town, which increase the risk of flooding in the urban area because it reduces the flow capacity. The culverts can be blocked by disposed garbage or accumulated sediment. During the site investigation in Isiolo Town, a lot of blocked culverts were spotted. One of the observed culverts is visible in Figure 9.3.

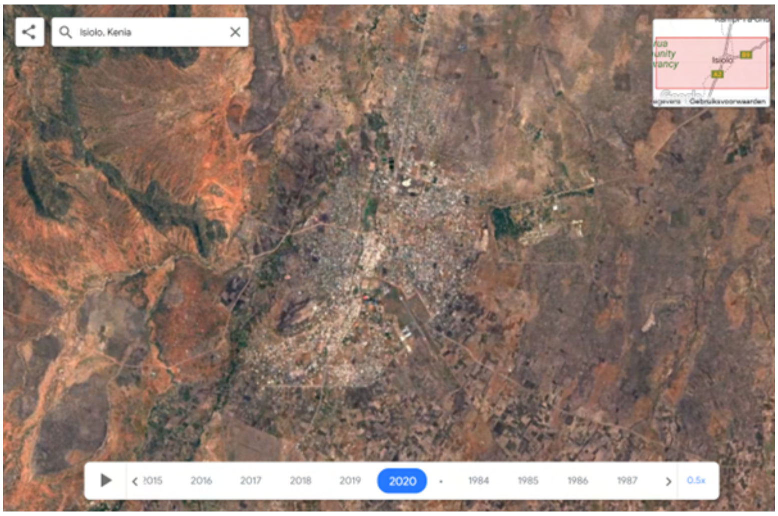
Figure 9.3: Blocked culvert in Isiolo Town, observed during the site investigation on October 4 2022.

Some other observed culverts can be seen in Appendix K. As visible in the pictures, many culverts are blocked by disposal which obstructs the flow, so water is unable to drain properly in case of a rainfall event.

Another increasing risk is the fact that Isiolo Town gets more and more densely built up area. The urbanisation is visible in the Figures 9.4, where Isiolo Town is visible in 2004 and 2020 by using the Timelapse function of Google Earth. In 2004 the urban area was 7.5 km^2 and in 2020 this area was already built up to 16.3 km^2. This growth rate is expected to remain the same for the upcoming years (MetaMeta, 2022).



(a) Isiolo Town in 2004



(b) Isiolo Town in 2020

Figure 9.4: Urbanisation of Isiolo Town 2004-2020 (Google Earth, n.d.)

Due to the increasing amount of paved area, there is less green area where water is able to infiltrate into the ground. As a result, the runoff increases which attributes to flooding. Also, there is limited surface water management in place and the storm water system in Isiolo is ill-maintained and it has not been designed to function as a network, resulting in a reduced drainage capacity. This insufficient drainage system leads to inundation even as a result of little rainfall (Republic of Kenya, 2013).

Another recent appearing contributing aspect to the increased risk related to more paved area have been the construction of the new airport and access road. This area is a raised area and it directs water into the flat Isiolo Town (Atkins, 2020). The airport area is one of 3 biggest factors of flood damage in Isiolo Town (Republic of Kenya, 2013). This change in water flow direction compared to the situation before construction is visualized as follows:

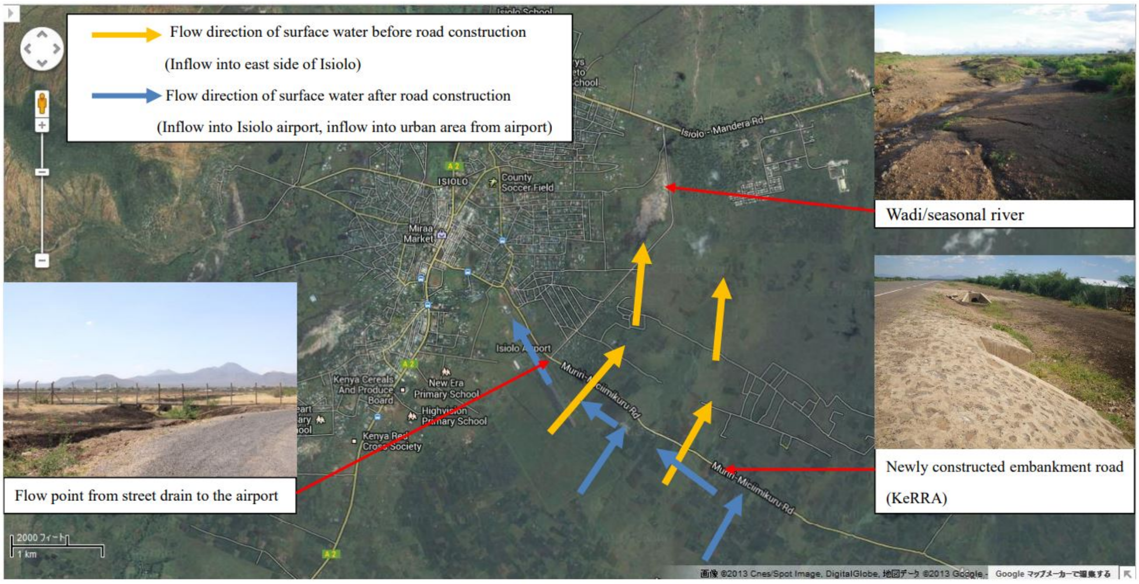


Figure 9.5: Direction of rain water from Airport area (Republic of Kenya, 2013).

The rapidly growing population in Isiolo Town also puts pressure on the existing sewerage systems. The population in the whole of Isiolo is expected to be 231,501 people in 2030 because of among other things Isiolo Town being the central hub of the LAPSSET project. The required sewerage capacity would then be 17,660 m3/day, although the capacity in time of realizing the National Water Master Plan in 2010 was only 2,000 m3/day. This shows the current urban drainage system is not sufficient to drain the wastewater (Nippon Koei Co., 2013).

All in all, the risk of flooding is considered to be high in the Isiolo River Basin, especially in Isiolo Town since this town is accompanied by many additional hazards. This high risk demands flood mitigation measures, from which the benefits will be evaluated in the resulting part of the report, after discussing the most recent state of flood related aspects within the basin by providing information gained from interviews and after simulating flood maps for different rainfall events in this chapter.

9.2 Recent rain events, floods, and current measures

Publicly available rainfall data online for the Isiolo River Basin is available for the period until 2011, prepared for the JICA team (Republic of Kenya, 2013). These findings were discussed in section 5.2 and it states the observed maximum daily rainfall for the period 1957-1989 for the station Isiolo DAO near Isiolo Town was 97 mm/day on March 10, 1982 (Republic of Kenya, 2013). The gained rainfall data from the TAHMO of the past 5 years shows a maximum daily rainfall of 103.7 mm/day on December 11 2019 for the station near Isiolo Town (van de Giesen et al., 2016). So the maximum daily rainfall which felt was already higher in just 5 years time than what felt in a period of 29 years (65 to 33 years ago, whereof 3 years of the period lacked data).

According to the WRA Isiolo, the last heavy floods have occurred 2 years ago in 2020. The floods happened in April/May and September. The cause was heavy rainfall in Mt. Kenya and other upstream parts (WRA Isiolo, personal communication, October 4 2022).

The WRUA Isiolo has also been interviewed about the last floods and their impact. The WRUA is a voluntary association, containing 21 members living in the Isiolo River Basin. All people from the community can join if they feel engaged and every zone has a representative. According to them, the last flood occurred in April 2017 with a duration of 2 hours as a result of a week of rainfall which felt upstream. Water filled up to the Mali Saba bridge, so in the rivers it filled up to 2 meters. In town the inundation had a depth of around 0.5 meters. Some mentioned also a water depth of 4 meters. This resulted in many damage, where most damage was done in town, since this is a flat area and all water is directed towards that area and many people are housed there. Also Galimara experienced much damage because there are many houses built there. Besides these residential areas, mainly cropland was damaged because that is located near the river. Also pipes were washed away and 250 trees and 20-30 livestock grazing next to the river were swept away. With regard to human life, 12 people died in Isiolo Town and 1 person outside town. Overall, these flood resulted in much damage. However, an important notice is that small flooding is used to irrigate land, especially upstream because the crops there (beans and maize) require more water, so it is not desired to withhold small flooding (WRUA Isiolo, personal communication, October 6 2022).

The WRA Isiolo discussed some mitigation measures they have implemented. They have implemented observation stations like rainfall gauging stations. However, many do not work anymore nowadays mostly due to vandalism. In addition, they have some river discharge measurements for the Isiolo River, but measuring is voluntary and manually, so often mistakes are made in the reading or it is not read at all. Besides these monitoring systems, they have implemented an Early Warning System in the past. The system warned when upstream an event of 60 mm/h of rainfall occurred. This enabled people in Isiolo Town and surroundings to evacuate in time. Also, there was a water level gauging station upstream with also the aim to warn people in time. However, both do not work anymore due to vandalism, malfunctioning, or bad maintenance. WRA Isiolo also states that when this measurement would be implemented once again, one should focus on the education disaster prevention so the whole community knows the importance and acknowledges the value of such systems. The current measures which are now in use in the Isiolo River Basin are mainly check dams upstream. These are small dams which redirect the stream or make the flow go slower. With regard to the future, WRA Isiolo expressed that they are now working on flood hazard mapping as a warning system. These maps must also indicate the inundation depth of floods (WRA Isiolo, personal communication, October 4 2022).

The WRUA expressed the usefulness of bamboo trees as flood mitigation measures since it mitigates the climate and has other benefits as well: it retains water, it cools the surroundings since it acts as a cover, it grows fast, animals do not destroy the tree because they do not like to eat the leaves, it purifies water, and it protects against erosion. However, other climate resilient tree species are hard to find since it must be able to deal with long periods of drought. Besides, it is of great importance that the trees do not attract human activity, so it must not be usable for example to feed livestock or as building material (WRUA Isiolo, personal communication, October 6 2022).

9.3 Results of flood maps with 3Di

The risk of floods is high in the Isiolo River Basin due to the contributing factors described in the risk assessment. 3Di includes the effect of some of this aspects described above, like the topographic gradient, and urban area, or other landuse. Several flood maps will be made based on questionnaires and the answers of the local parties. Other scenarios are also considered. The data set provided for the JICA in the Integrated Flood Management Plan for the Isiolo River Basin and the obtained data set of daily rainfall from the TAHMO from September 2017- September 2022 is examined to find rainfall for several return periods. Also, climate change is taken into consideration. Intentionally the results would have been validated with data obtained from discharge measurements in the Isiolo or Marania River. As no current or available data was given validation has been done on the basis of interviews done with local community of Isiolo, the WRUA of Isiolo Watershed and the WRA of Isiolo County.

9.3.1 Flood maps with 60 mm/h rainfall upstream

As discussed in section 9.2, the WRA Isiolo has told in interviews that they used to have an early warning system which warns when the rainfall upstream exceeds 60 mm/h. The typical duration of such a rain event would be 2 hours long (WRA Isiolo, personal communication, October 4 2022). Therefore, a rain event of 60 mm/h for 2 hours upstream of the examined river basin is modelled in 3Di. The resulting flood map is as follows:

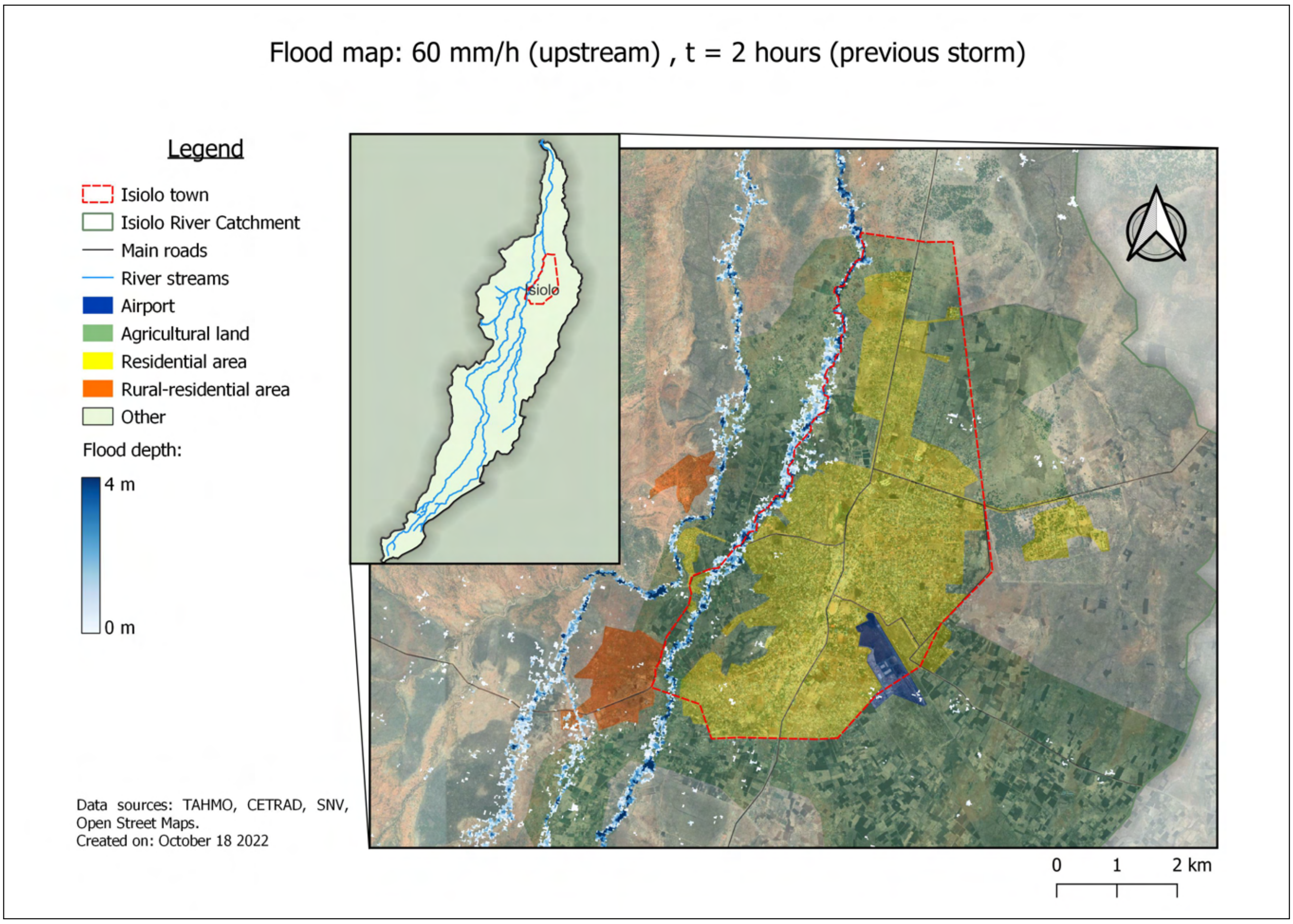


Figure 9.6: Flood map of 60 [mm/h] intensity storm (duration: 2 hours) created in 3Di, zoomed in on Isiolo Town

9.3.2 Flood maps for different return periods of rainfall

To calculate the daily rainfall for different return periods, the methods Annual Maxima and Peak Over Threshold are used. The formulas were already given in section 7.6.2. The results of rainfall for different return periods will be given in this section. The calculated intensities are a result of considering two duration lengths: 1 hour and 3 hours, where a duration of 3 hours results in a smaller intensity. These intensities are used as input to make flood maps with 3Di which will be shown after the calculation of the rainfall.

Calculation rainfall intensities

Annual Maxima
For the Annual Maxima method, the data gained by the JICA (received from the KMD) is used. This is annual maximum daily rainfall data for the Timau Marania Station and the Isiolo DAO station. This data is a bit outdated, but since it contains many years of rainfall data (32 years for Timau Marania and 29 years usable years for Isiolo DAO station) it can definitely give a valid indication of rainfall intensities for different return periods. Besides, as mentioned before, the KMD has told the rainfall gauging stations are not in operation anymore for at least 10 years now. The data set can also be used to compare with the POT method which is used for the past 5 years with the data from TAHMO because the Isiolo DAO station is located very near the TAHMO Isiolo station. The locations of the stations and the data set of the stations are indicated in Appendix L.

Timau Marania Station
For the Timau Marania Rainfall Gauging Station, JICA was provided with data from 1957-1988, gained from the KMD. This data can be found in Appendix L, Figure 2.
By using the Equations of 7.3, the daily rainfall X can be found for the different return periods with μ = 65.03125, σ = 22.68049, β = 17.68391, and X_0 = 54.8241. It has been chosen to look at the return period for T = 2, 5, 10, 20 , 30, 50, and 100 years because this overlaps with some return periods where te JICA has performed its calculation for so it enables one to compare the results (Republic of Kenya, 2013). The results are given in Table 9.1 below:

Table 9.1: Rainfall for different return periods and its intensities for different durations as a result of Annual Maxima, Timau Marania Station.

Return period T (years)	**2**	**5**	**10**	**20**	**30**	**50**	**100**
Rainfall X (mm/day)	61.30548	81.3489	94.61939	107.3488	114.6717	123.8256	136.1727
Intensity (mm/h) **for duration of 1h**	61.30548	81.3489	94.61939	107.3488	114.6717	123.8256	136.1727
Intensity (mm/h) **for duration of 3h**	20.43516	27.1163	31.5398	35.78292	38.22388	41.27521	45.39091
JICA X (mm/day)		81.6	95.1	108	115.4	124.7	
Difference Rainfall X and JICA X		-0.2511	-0.48061	-0.65124	-0.72835	-0.87438	

The results gained by the JICA team where they used the same data set from the same station and the Jack Knife estimate are also presented in Table 9.1 and are very similar to the results with the Annual Maxima method. Just as with the Annual Maxima, the Gumbel distribution is used as probability distribution model in the results of the JICA. Since the results for all return periods differ maximally 1 mm/day, it is assumed that the Annual Maxima method is reliable and therefore this method is also used for Isiolo DAO Station, for which the JICA team has not performed a calculation.

Isiolo DAO Station

The JICA team has not performed the extreme value analysis for the Isiolo DAO Rainfall Gauging Station, but the same calculation with Annual Maxima is done for this station with the data set given in Appendix L, Figure 3, which shows annual maximum daily rainfall for the period 1957-1988. Three years are excluded from the calculation since there was no annual maximum obtained in these years. With $\mu = 56.53448276$, $\sigma = 18.5253933$, $\beta = 14.4441899$, and $X_0 = 48.19729635$ the results are given in Table 9.2 below:

Table 9.2: Rainfall for different return periods and its intensities for different durations as a result of Annual Maxima, Isiolo DAO station.

Return period T (years)	**2**	**5**	**10**	**20**	**30**	**50**	**100**
Rainfall X (mm/day)	53.49128	69.86271	80.70203	91.09936	97.08069	104.5576	114.6427
Intensity (mm/h) **for duration of 1h**	53.49128	69.86271	80.70203	91.09936	97.08069	104.5576	114.6427
Intensity (mm/h) **for duration of 3h**	17.83043	23.28757	26.90068	30.36645	32.36023	34.85255	38.21424

The location of this rainfall gauging station is very similar to the rainfall station of TAHMO of which data is available for the past 5 years, for which calculations will be done with Peak Over Threshold.

Peak Over Threshold

Isiolo TAHMO TA00172 Station

As stated before in chapter 7.6.2, POT is desired when the amount of years of available data is small, which is the case for the data from TAHMO which only includes data from the past 5 years (September 2017- September 2022) for Isiolo Town, station TA00172. The location of this station is indicated in Appendix L, Figure 4. The annual daily maximum rainfall can also be found in this Appendix, including the missing amount of measured days per year. The years are considered from September till September due to the nature the data has been given by TAHMO.

As explained in 7.6.2 it has been chosen to select the threshold by 2 different methods: 1. Langbein and 2. Madsen. For Langbein the result of the threshold is shown in Table 9.3 and for Madsen the result of the threshold value is shown in Table 9.4.

Table 9.3: Result of the chosen threshold using the Langbein method

Langbein method		
Data obtainded from:	Tahmo	(van de Giesen et al., 2016)
Data period from: 1-sep-17 to 01-Sep-22		
YEAR	DATE	Maximum Daily Rainfall [mm/day]
Sep-2017 to Sep-2018	07-Nov-17	24.939
Sep-2018 to Sep-2019	03-Jun-19	36.783
Sep-2019 to Sep-2020	11-Dec-19	103.7
Sep-2020 to Sep 2021	07-Dec-20	59.317
Sep-2021 to Sep2022	17-Jan-22	53.482
Chosen Threshold (ϵ)	24.939	mm/day

Table 9.4: Result of the chosen threshold using the Madsen method

Madsen method		
Data obtainded from:	Tahmo	(van de Giesen et al., 2016)
Data period from: 1-sep-17 to 01-Sep-22		
Parameter	Symbol	Value obtained from whole date period
Mean all data	μ	1.8555545
Standard devaition all data	σ	6.7116915
Standard Frequency Factor	k	3
Chosen Threshold (ϵ)	21.99063	mm/day

The outcome of both methods for calculating the threshold is quite similar. By using the Langbein method to select a threshold, the value is 24.939. By using the Madsen method to select a threshold, the value is 21.9906. With these thresholds the data which are above the threshold can be filtered to include in the calculation with POT. The Langbein-threshold leads to the data presented in Table 9.5 and the Madsen-threshold leads to the data in the Table 9.6.

Table 9.5: Data above Threshold from Isiolo TAHMO TA00172 Station using Langbein method

Langbein		
Threshold (ϵ):		24.939
Number of data above threshold (n): 21		
Year	Date	Precipitation [mm/day]
17/18	7-nov-17	24.939
18/19	12-nov-18	28.884
18/19	29-nov-18	25.465
18/19	3-jun-19	36.783
19/20	1-sep-19	29.539
19/20	23-nov-19	52.464
19/20	25-nov-19	30.421
19/20	9-dec-19	57.279
19/20	11-dec-19	103.7
19/20	27-jan-20	26.145
19/20	26-mrt-20	25.241
19/20	15-apr-20	36.174
19/20	20-apr-20	52.821
20/21	29-sep-20	37.475
20/21	9-okt-20	29.938
20/21	7-dec-20	59.317
20/21	8-dec-20	27.529
21/22	17-jan-22	53.482
21/22	18-mrt-22	40.599
21/22	25-mrt-22	31.38
21/22	16-apr-22	33.489

Table 9.6: Data above Threshold from Isiolo TAHMO TA00172 Station using Madsen method

Madsen		
Threshold (ϵ):		21.9906
Number of data above threshold (n): 29		
Year	Date	Precipitation [mm/day]
17/18	7-nov-17	24.939
18/19	12-nov-18	28.884
18/19	29-nov-18	25.465
18/19	14-dec-18	23.073
18/19	20-mrt-19	24.343
18/19	23-apr-19	22.549
18/19	3-jun-19	36.783
19/20	1-sep-19	29.539
19/20	23-nov-19	52.464
19/20	25-nov-19	30.421
19/20	9-dec-19	57.279
19/20	11-dec-19	103.7
19/20	27-jan-20	26.145
19/20	30-jan-20	24.41
19/20	1-feb-20	22.015
19/20	26-mrt-20	25.241
19/20	15-apr-20	36.174
19/20	20-apr-20	52.821
19/20	11-aug-20	22.936
20/21	15-apr-20	37.475
20/21	20-apr-20	29.938
20/21	11-aug-20	59.317
20/21	8-dec-20	27.529
21/22	17-jan-22	53.482
21/22	26-feb-22	23.493
21/22	18-mrt-22	40.599
21/22	25-mrt-22	31.38
21/22	29-mrt-22	23.01
21/22	16-apr-22	33.489

With these data sets depending on the threshold, the parameters for the POT can be calculated by using the Equations provided in section 7.6.2. The results for both methods of finding a threshold value are as follows:

Table 9.7: Outcomes of POT formulas using data shown in Table 9.5 & 9.6

	Langbein	Madsen
μ	40.1459	35.4791
σ	18.4503	17.3936
n	21	29
$\sum(X_i - \epsilon)$	319.3452	391.1648
β	15.2069	13.4884

With these parameters now known, the POT-formulas provided in equation 7.9, 7.10, and 7.12 can be used to calculate the amount of daily precipitation for a certain return period. In Table 9.8 and 9.9 the result of the expected daily rainfall for a given return period are shown for both methods of finding a threshold value:

Table 9.8: Rainfall for different return periods and its intensities for different durations as a result of Peak Over Threshold using Langbein, Isiolo TAHMO TA00172 Station.

Return period T (years)	**2**	**5**	**10**	**20**	**30**	**50**	**100**
Rainfall X with Langbein (mm/day)	57.30282814	71.23678	81.77741	92.31804339	98.483917	106.252	116.7926
Intensity (mm/h) **for duration of 1h**	57.30282814	71.23678	81.77741	92.31804339	98.483917	106.252	116.7926
Intensity (mm/h) **for duration of 3h**	19.10094271	23.74559	27.25914	30.77268113	32.827972	35.41733	38.93088

Table 9.9: Rainfall for different return periods and its intensities for different durations as a result of Peak Over Threshold using Madsen, Isiolo TAHMO TA00172 Station.

Return period T (years)	**2**	**5**	**10**	**20**	**30**	**50**	**100**
Rainfall X with Madsen (mm/day)	55.05086419	67.4102	76.75967	86.1091451	91.578237	98.46848	107.818
Intensity (mm/h) **for duration of 1h**	55.05086419	67.4102	76.75967	86.1091451	91.578237	98.46848	107.818
Intensity (mm/h) **for duration of 3h**	18.35028806	22.47007	25.58656	28.70304837	30.526079	32.82283	35.93932

When one compares these results from POT of 5 years with the results in Table 9.2 which was gained with AM of 29 years for approximately the same location, the rainfall tends to be slightly higher for the same return period when using Langbein threshold. But when using the Madsen threshold, the rainfall is found to be generally lower for the same return period compared to calculation with AM, with exception of T=2 years. However, both results are very debatable since the huge amount of missing data, as one can see in the Appendix L. In total, 617 days of data are missing. This also includes missing data in the rainy seasons which could definitely include maximum daily rainfall for a year. Therefore, the results are definitely not very accurate. But since it can be expected that as a result of climate change the return period of extreme events reduces, or in other words the rainfall increases for the same return period (as discussed in section 4.3), the flood maps with the input from rainfall in Isiolo Town will be made for the intensities with POT using Langbein because these rainfall values are the highest and higher than intensities gained from the more outdated data set of the Isiolo DAO Station. So the values which are shown in Table 9.8, which are based on the TAHMO data set, are used to make flood maps.

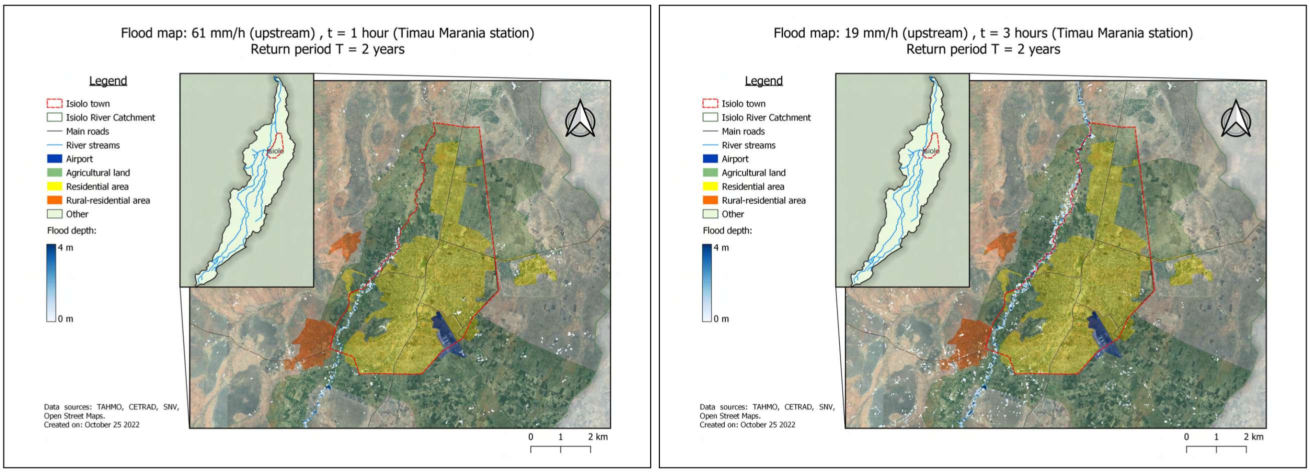
Resulting flood maps for different return periods of rainfall

To produce flood maps, there is looked into extreme events with T=2 and T=5 years since the SLAMDAM is mainly a temporary and emergency measure, which can be deployed quickly. Therefore, the smaller return periods are of more interest, since for larger return periods permanent water structures would probably be a more obvious choice. Besides, the SLAMDAM has a lifetime of at least 40 years which is quite long, but more probable not of interest for rainfall intensities with a return period of more than these 40 years.
These return periods have also been chosen for validation purposes. Several institutions in the Isiolo River Basin were asked about the last severe floods in the past 5 years. So this includes floods with a return period of 2 and 5 years. The water height they mentioned can be used for validation of the flood maps for T=2 and T=5. During the WRUA interview many people living within the whole basin were present and answers were divided from 0.5 meters in Isiolo Town to 4 meters outside the town. With this in mind and the validation of arrival time in chapter 10.3.1 the flood maps in this section can be confirmed to be close to reality.

Timau Marania Station

The results of the intensities, shown in Table 9.1, are used to provide flood maps. The Timau Marania Station is stationed upstream of the river basin, therefore local rain is modelled in 3Di through the use of rainfall interception, as explained in chapter 7. Modelling of this local rain upstream is valuable because it has become clear from interviews that flooding is often the result from a rain event from upstream. It does not need to rain in Isiolo Town itself to result in flooding in the town.

For T=2, so an intensity of 61 mm/d, with a duration of 1h resulting in 61 mm/h and a duration of 3h resulting in 19 mm/h, the following flood maps ate the result:

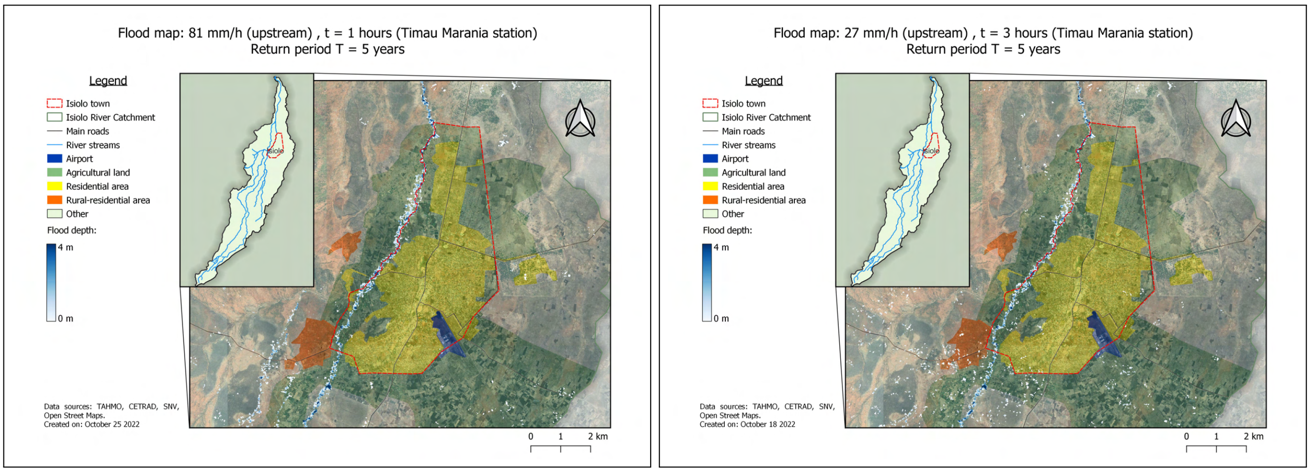


(a) Flood map of 61 [mm/h] intensity storm (duration: 1 hour) created in 3Di, zoomed in on Isiolo Town

(b) Flood map of 19 [mm/h] intensity storm (duration: 3 hours) created in 3Di, zoomed in on Isiolo Town

Figure 9.7: Result for rain intensities with 2 year return period. For full Figures see M

For T=5, so an intensity of 81 mm/d, with a duration of 1h resulting in 81 mm/h and a duration of 3h resulting in 27 mm/h, the following flood maps are the result:



(a) Flood map of 81 [mm/h] intensity storm (duration: 1 hour) created in 3Di, zoomed in on Isiolo Town

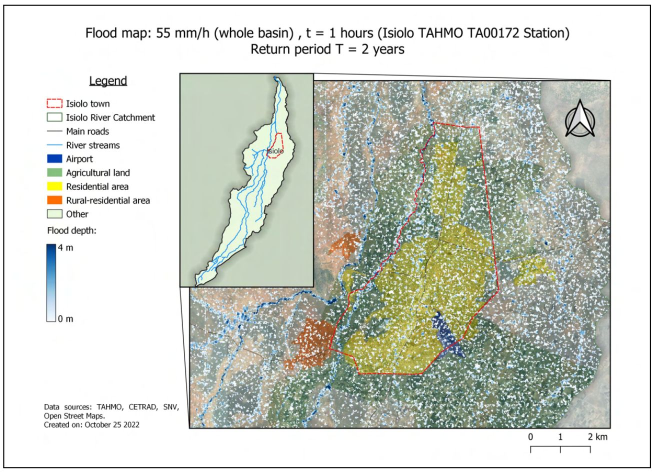
(b) Flood map of 27 [mm/h] intensity storm (duration: 3 hours) created in 3Di, zoomed in on Isiolo Town

Figure 9.8: Result for rain intensities with 5 year return period. For full Figures see M

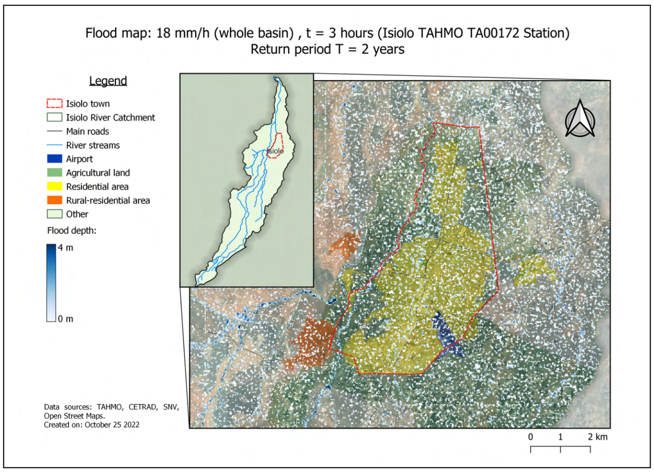
Station Isiolo Town

For rainfall input in Isiolo Town, the results shown in Table 9.8 are used to produce flood maps. The same intensity of the rainfall is modelled over the whole river basin.

For T=2, so an intensity of 55 mm/d, with a duration of 1h resulting in 55 mm/h and a duration of 3h resulting in 18 mm/h, the following flood maps are the result:



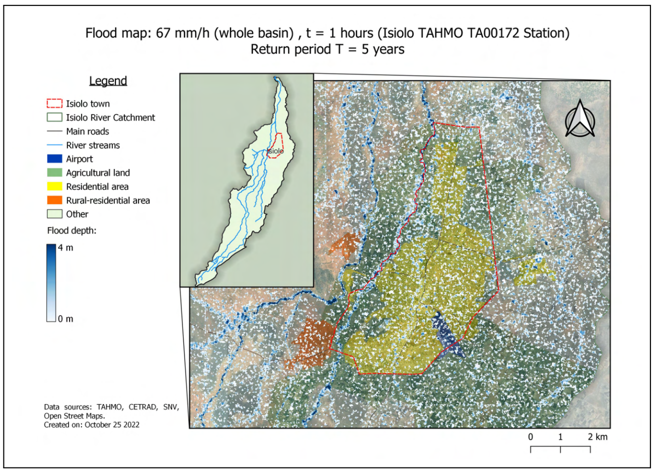
(a) Flood map of 55 [mm/h] intensity storm (duration: 1 hour) created in 3Di, zoomed in on Isiolo Town



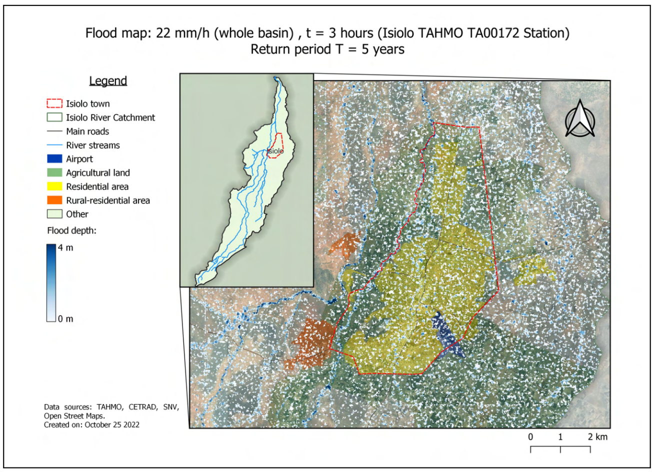
(b) Flood map of 18 [mm/h] intensity storm (duration: 3 hours) created in 3Di, zoomed in on Isiolo Town

Figure 9.9: Result for rain intensities with 2 year return period. For full Figures see M

For T=5, so an intensity of 67 mm/d, with a duration of 1h resulting in 67 mm/h and a duration of 3h resulting in 22 mm/h, the following flood maps are the result:



(a) Flood map of 67 [mm/h] intensity storm (duration: 1 hour) created in 3Di, zoomed in on Isiolo Town



(b) Flood map of 22 [mm/h] intensity storm (duration: 3 hours) created in 3Di, zoomed in on Isiolo Town

Figure 9.10: Result for rain intensities with 5 year return period. For full Figures see M

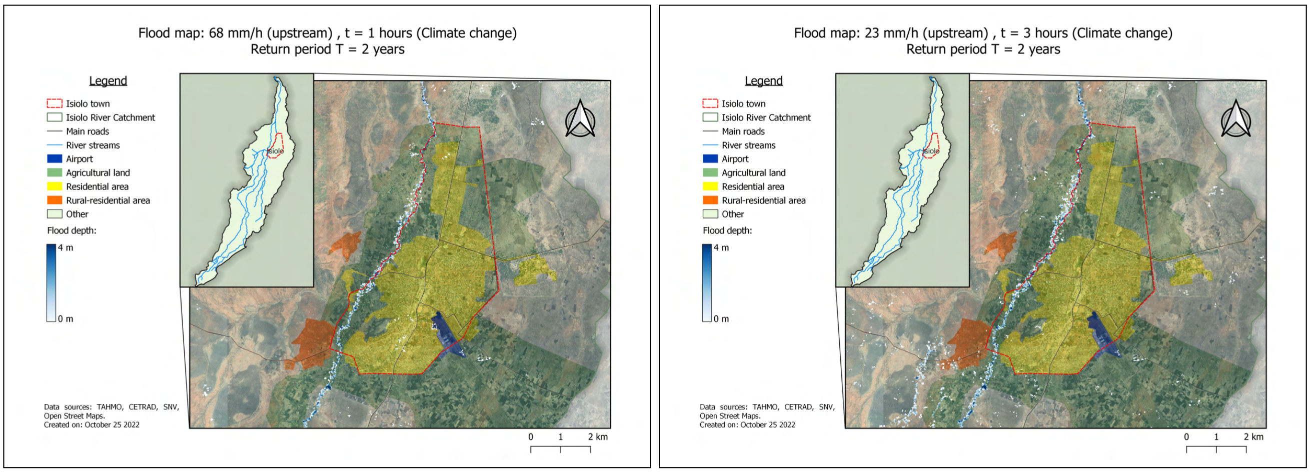
9.3.3 Flood maps including climate change predictions

As visible in Table 4.2, the mean annual precipitation of the ENN basin will increase with 10.9 % in the period 2018-2050. Since the Isiolo River Basin is located in this basin and there are no more accurate predictions for smaller basins in particular, this percentage change is used as a prediction for the Isiolo River Basin as well. However, it must be noted that this percentage increase is stated for the mean annual instead of the annual maximum daily and for another more recent period (2018-2050), but nevertheless this percentage is used since it is the only available climate change prediction and will be used to map climate change-induced flooding. As discussed in section 9.2, the WRA and WRUA have made clear that floods in Isiolo Town are mostly the result of rainfall falling upstream which is directed towards the flat Isiolo Town. Timau Marania Station is located upstream in the Isiolo River Basin, so the climate change effect will be implemented for this rainfall data. The results are, by multiplying all maximum daily rainfall for every year in the period 1957-1988 by 1.109, with as result μ = 72.11965625, σ = 25.15266761, β = 19.61145448, and X0 = 60.79992473:

Table 9.10: Rainfall for different return periods and its intensities for different durations as a result of climate change +10.9% and Annual Maxima, Timau Marania Station.

Return period T (years)	**2**	**5**	**10**	**20**	**30**	**50**	**100**
Rainfall X (mm/day)	67.98778	90.21593	104.9329	119.0498	127.1709	137.3226	151.0155
Intensity (mm/h) **for duration of 1h**	67.98778	90.21593	104.9329	119.0498	127.1709	137.3226	151.0155
Intensity (mm/h) **for duration of 3h**	22.66259	30.07198	34.97763	39.68326	42.39029	45.77421	50.33851

For T=2, so an intensity of 68 mm/d, with a duration of 1h resulting in 68 mm/h and a duration of 3h resulting in 23 mm/h, the following flood maps are the result:

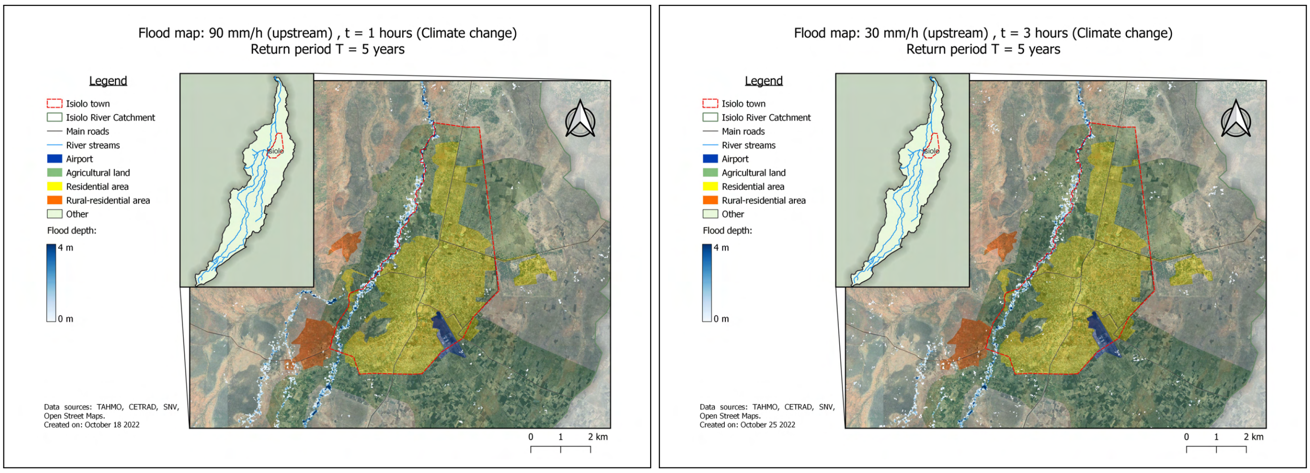


(a) Flood map of 68 [mm/h] intensity storm (duration: 1 hour) created in 3Di

(b) Flood map of 23 [mm/h] intensity storm (duration: 3 hours) created in 3Di

Figure 9.11: Result for rain intensities with 2 year return period after climate change. For full Figures see M

For T=5, so an intensity of 90 mm/d, with a duration of 1h resulting in 90 mm/h and a duration of 3h resulting in 30 mm/h, the following flood maps are the result:



(a) Flood map of 90 [mm/h] intensity storm (duration: 1 hour) created in 3Di

(b) Flood map of 30 [mm/h] intensity storm (duration: 3 hours) created in 3Di

Figure 9.12: Result for rain intensities with 5 year return period after climate change. For full Figures see M

Chapter 10

Feasibility SLAMDAM

This chapter will discuss the possible implementation of the SLAMDAM. The flood maps provided in the previous chapter have shown where the water level will be the highest as a result of rainfall events when considering different scenarios. In this chapter, the flood maps will be used as input for the FIS Tool and the FIS Tool will be used to indicate the benefits of the SLAMDAM when it is deployed at a certain location. Some of the locations which are recommended due to this method are also verified by a site visit to see whether the implementation of the SLAMDAM is really possible at that location with regard to soil, presence of water, and other aspects as discussed in chapter 6.

10.1 Feasibility implementation SLAMDAM

To evaluate the relevance of the SLAMDAM, the possible rainfall scenarios and corresponding water depths have to be known. As mentioned before, the 3Di tool is used for this and the results are provided in section 9.3. Following this, a costs and benefit analysis can be made in the FIS Tool to see how SLAMDAM can reduce consequences induced by flood events. Simultaneously the suitability of the SLAMDAM has to be evaluated or in other words: the boundary conditions have to be set. The boundary conditions depend on logistics, ground conditions, strength, dimensions, and community support. An overview of the SLAMDAM deployment chart can be found in Figure 10.1. It is needed to determine the effectiveness as well as the suitability to decide if it is possible to deploy SLAMDAM.

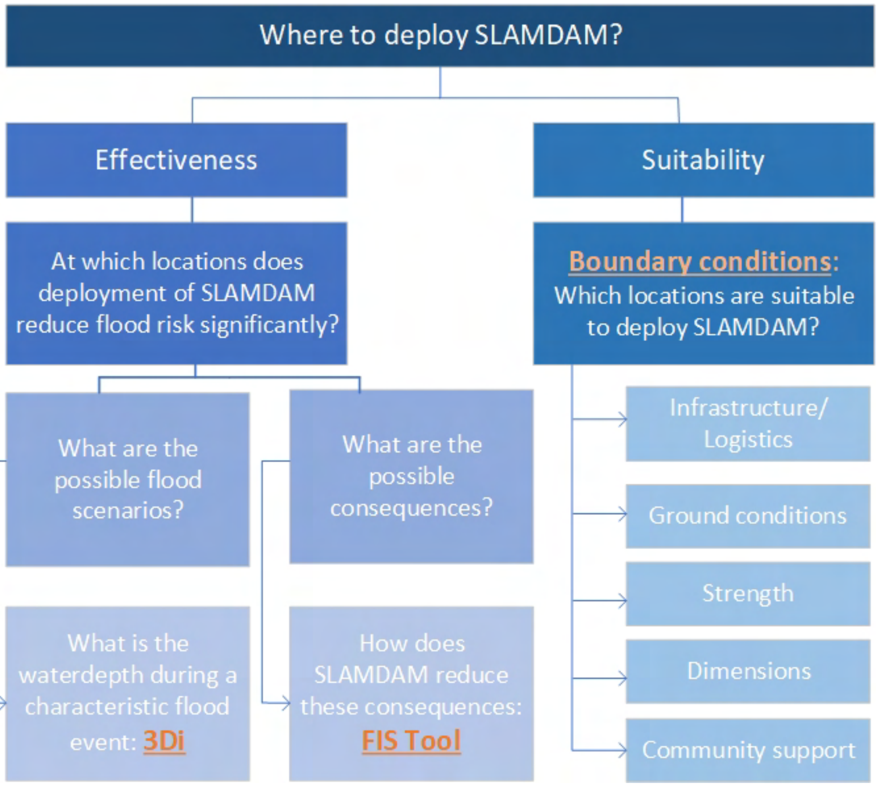


Figure 10.1: SLAMDAM deployment chart

10.2 Results of the FIS Tool

The flood maps for different scenarios can be implemented in the FIS Tool to indicate the provided benefits as a result of certain mitigation measures. The height of the SLAMDAM, which is 1 meter, can be implemented in the FIS Tool. If the water exceeds a height of 1 meter, overtopping will occur. The location of the SLAMDAM and its length can be adjusted until the outcome of the benefit is the best. This benefit can make a distinction between protecting agriculture or the residential area. For the different scenarios discussed in section 9.3, the benefit is calculated for relevant scenarios as input. These calculated benefits can be used to compare different locations to implement the SLAMDAM. The focus can be either on protecting the agriculture or the residential area, so mainly Isiolo Town.
So with the FIS Tool it will be possible to compute the benefit from implementing the mitigation measure. For agricultural areas there is looked into the protected area in square meters per meter SLAMDAM. This is because the FIS Tool currently does not take crop losses into account in agricultural areas, and the damages are solely based on damage to the surface, resulting in an underestimation of the real damages. The residential areas can be analyzed in monetary value, and the benefits will be translated to a unit of prevent damages per meter of SLAMDAM. The SLAMDAM will prove to be beneficial when the benefits of prevented damage per meter SLAMDAM is higher than the cost of a meter of SLAMDAM. From Zephyr Consulting it is currently known that the price for a 5 meters long and 1 meter high unit costs approximately 2300 euros, which means that 1 metre of SLAMDAM is equivalent to 460 euros. Since the SLAMDAM can be used multiple times, it is expected that the aggregated benefit of prevented damages will overcome the initial investment of the SLAMDAM.

10.2.1 60 mm/h rainfall upstream

Section 9.3.1 has provided a flood map for a rain event of 60 mm/h, which was based on the fact that there used to be an Flood Early Warning System in operation which alerted inhabitants of the town whenever a rain event of 60 mm/h occurred upstream of the town. It is interesting to investigate where the SLAMDAM can be deployed the moment the FEWS gives an alert for flooding. Different locations to implement the SLAMDAM can be determined following the flood map as shown in section 9.3.1. The location of the SLAMDAM depends on whether it is desirable to protect agricultural land or residential areas. Potential locations where the SLAMDAM can be implemented for both agricultural and residential protection, are shown below:

(a) Flood map displayed in FIS Tool Interface

(b) Agricultural land protected from 1 meter water depth

(c) Residential area protected from 1 meter water depth

Figure 10.2: Potential locations for SLAMDAM implementation in a 60 $mm/hour$ storm, t = 2 hours

The flood map shown in Figure 10.2a shows a stream splitting up into two separate streams overland. The idea of placing a SLAMDAM at the first junction of the stream would ideally divert the flow from one of the streams into the other one. The left stream flows over a less occupied terrain. Placing the SLAMDAM in the right place would therefore protect the whole right stream from 1 meter flood depths. This section is predominantly agricultural land, hence the placement of the SLAMDAM for this location serves for agricultural protection. The SLAMDAM placed for residential protection purposes, is expected to protect the area shown in Figure 10.2c. Tables 10.1 & 10.2 below show the agricultural and residential benefit for the proposed locations.

Table 10.1: Agricultural benefit for 60 mm/h (t = 2 hours) rain event

Rain event $[mm/h]$	Benefit (in Area $[m^2]$)	Meters SLAMDAM used	Protected Area/meter SLAMDAM $[m^2]$
60	61,600	300	205

Table 10.2: Residential benefit for 60 mm/h (t = 2 hours) rain event

Rain event $[mm/h]$	Benefit (in [€])	Meters SLAMDAM used	Benefit per meter SLAMDAM [€]
60	214,836	850	252.75

10.2.2 Different return periods of rainfall

Timau Marania Station

For the Timau Marania Station, there where flood maps for 4 rain events given in section 9.3.2. These flood maps showed that the rain event of 81 mm/h for a duration of 1 hour and the event of 27 mm/h for a duration of 3 hours were the most interesting as these flood maps have both showed floods in the East-Marania river. These flood maps have been implemented in the FIS Tool and for these rain events different locations have been located where it is likely a flood will occur. One mitigation measures (Figure 10.3c) is to protect residential area and one mitigation measure to protect agricultural land (Figure 10.3b)

(a) Flood map 81 [mm/h] displayed in FIS Tool Interface

(b) Agricultural land protected from 1 meter water depth

(c) Residential area protected from 1 meter water depth

Figure 10.3: Potential locations for SLAMDAM implementation for the 81 and 27 mm/h storms calculated from Timau Marania Station data

For the residential and agricultural area a location in the North-West of Isiolo Town has been chosen to protect with the SLAMDAM. This part of the East Marania river is prone to flooding during the storm events and lies next to both types of area. If a SLAMDAM would be used next to this river the area shown in Figure 10.3b would be protected for floods up to 1 meter. On the residential side less SLAMDAM needs to be used to protect a certain area. In Table 10.3 & 10.4 the benefit of each mitigation measure for the different events are shown. The agriculture part is given in protected Agricultural area per meter SLAMDAM because loss in crops is not taken into account in the FIS Tool. The residential area is shown in Benefit per meter SLAMDAM, to compare the prevented benefit against the amount of SLAMDAM used. One can see here that the benefit of 1 meter SLAMDAM is lower than the cost of a SLAMDAM, but this is just for 1 storm event. If 2 separate storm events would happen, the benefit would already be higher.

Table 10.3: Agricultural benefit

Rain event $[mm/h]$	Benefit (in Area $[m^2]$)	Meters SLAMDAM used	Protected Area/meter SLAMDAM $[m^2]$
81	8,400	620	13.55
27	7,600	620	12.26

Table 10.4: Residential benefit

Rain event $[mm/h]$	Benefit (in [€])	Meters SLAMDAM used	Benefit per meter SLAMDAM [€]
81	136,486	330	413.59
27	119,517	330	362.17

Station Isiolo Town

From the floodmaps created with the data from the station Isiolo Town, which created a rain event that does not fall locally upshed but falls equally in the watershed, the most important rain events are from 67 mm/h (1 hour storm) & and 22 mm/h (3 hour storm). These flood maps have more small puddles in the area due to the rain happening in the whole region. In Figure 10.4a the flood map of the 67 mm/h rain event is shown.

(a) Flood map 67 [mm/h] displayed in FIS Tool Interface

(b) Agricultural land protected from 1 meter water depth

(c) Residential area protected from 1 meter water depth

Figure 10.4: Potential locations for SLAMDAM implementation for the 67 and 22 mm/h storms calculated from Station Isiolo Town data

For these rain events it has been chosen to have a mitigation measure protecting the agricultural area (Figure 10.4b) near the middle of Isiolo Town at the East Marania river. In this place there is a lot of agricultural land next to the river and with a relatively small SLAMDAM a big area could be protected. For the urban mitigation area it has been chosen to use a big SLAMDAM near the airport to function as a water retention basin (see Figure 10.4c). Figure 9.5 already showed that if there is a rain event at/near the airport the rainwater will flow towards and over the airport to Isiolo Town, creating urban floods in town. With the SLAMDAM barrier a water retention area can be created to reduce flooding in the town area. The amount of protected area and benefit depends highly on location of the area and amount of SLAMDAM used with a water retention function. It has been chosen to follow the blue arrows in Figure 9.5.

Table 10.5: Agricultural benefit

Rain event $[mm/h]$	Benefit (in Area $[m^2]$)	Meters SLAMDAM used	Protected Area/meter SLAMDAM $[m^2]$
67	11,600	560	20.71
22	5,200	560	9.29

Table 10.6: Residential benefit

Rain event $[mm/h]$	Benefit (in [€])	Meters SLAMDAM used	Benefit per meter SLAMDAM [€]
67	358,256	980	365.57
22	281,234	980	286.97

10.2.3 Climate change predictions

From the previous chapter it has been established that the normative rain events for durations of 1 hour and 3 hours, are rain events of 90 mm/h and 30 mm/h respectively. These are projected rain events to occur as a result of climate change, both with a return period of T = 5 years. From the acquired flood maps, a potential suitable location for the SLAMDAM can be determined. The locations (whether it is to protect agricultural land or residential areas) for both rain events are depicted below:

(a) Flood map displayed in FIS Tool Interface

(b) Agricultural land protected from 1 meter water depth

(c) Residential area protected from 1 meter water depth

Figure 10.5: Potential locations for SLAMDAM implementation in a 30 mm/h storm, t = 3 hours

(a) Flood map displayed in FIS Tool Interface

(b) Agricultural land protected from 1 meter water depth

(c) Residential area protected from 1 meter water depth

Figure 10.6: Potential locations for SLAMDAM implementation in a 90 mm/h storm, t = 1 hour

Both rain events show similar flood maps. Therefore, the same SLAMDAM locations have been proposed for agricultural and residential protection. Despite the amount of total rainfall being the same, it is noticeable that the more concentrated event (so a duration of 1 hour) produces higher flood depths (Figure 10.5 & 10.6). It is therefore interesting to see how much each event differs in possible protection. The following Tables 10.7 & 10.8 show the computed benefit for the two rain events:

Table 10.7: Agricultural benefit for 30 mm/h (t = 3 hours) and 90 mm/h (t = 1 hour) rain event

Rain event [mm/h]	Benefit (in Area [m^2])	Meters SLAMDAM used	Protected Area/meter SLAMDAM [m^2]
30	22,800	1200	19
90	30,800	1200	25.67

Table 10.8: Residential benefit for 30 mm/h (t = 3 hours) and 90 mm/h (t = 1 hour) rain event

Rain event [mm/h]	Benefit (in [€])	Meters SLAMDAM used	Benefit per meter SLAMDAM [€]
30	83,367	350	238.19
90	96,941	350	276.97

These results provide recommendations for locations of the implementation of the SLAMDAM.

10.2.4 Recommended locations for the SLAMDAM as a result of the FIS Tool

The locations for deployment of the SLAMDAM as a result of the outcome of the FIS Tool, so which result in most benefit, are shown in Figures 10.7, 10.8, 10.9.

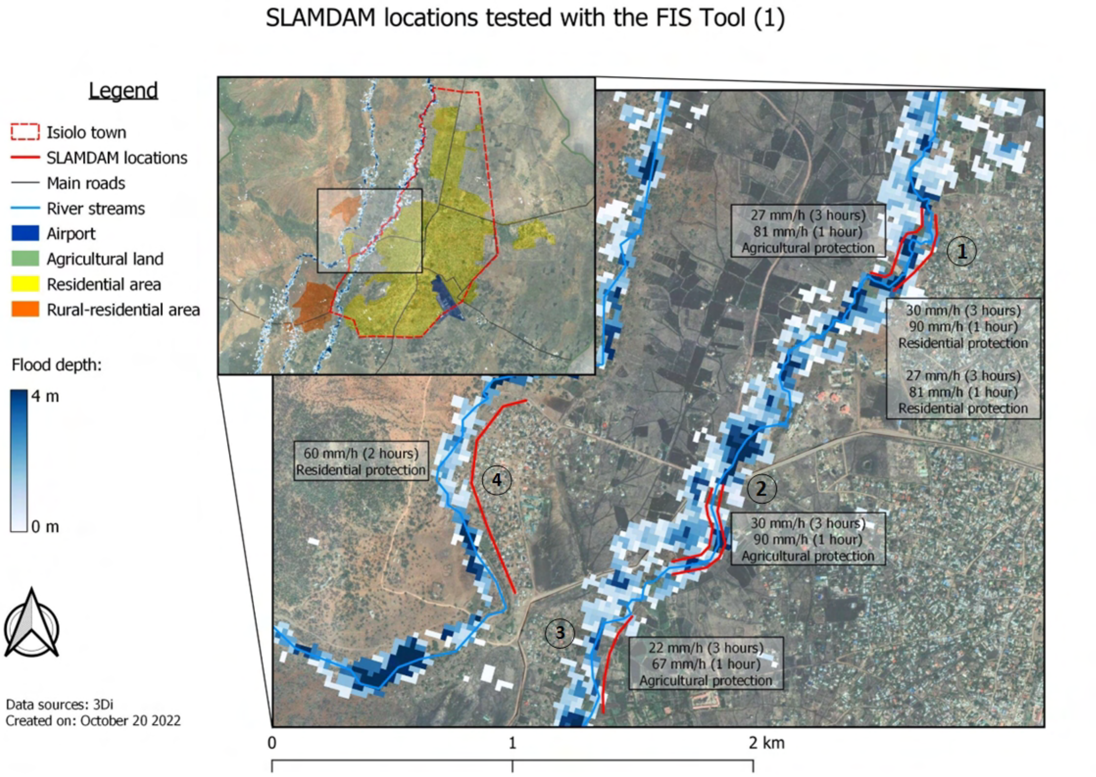


Figure 10.7: Possible locations for implementing the SLAMDAM based on FIS Tool simulations (1)

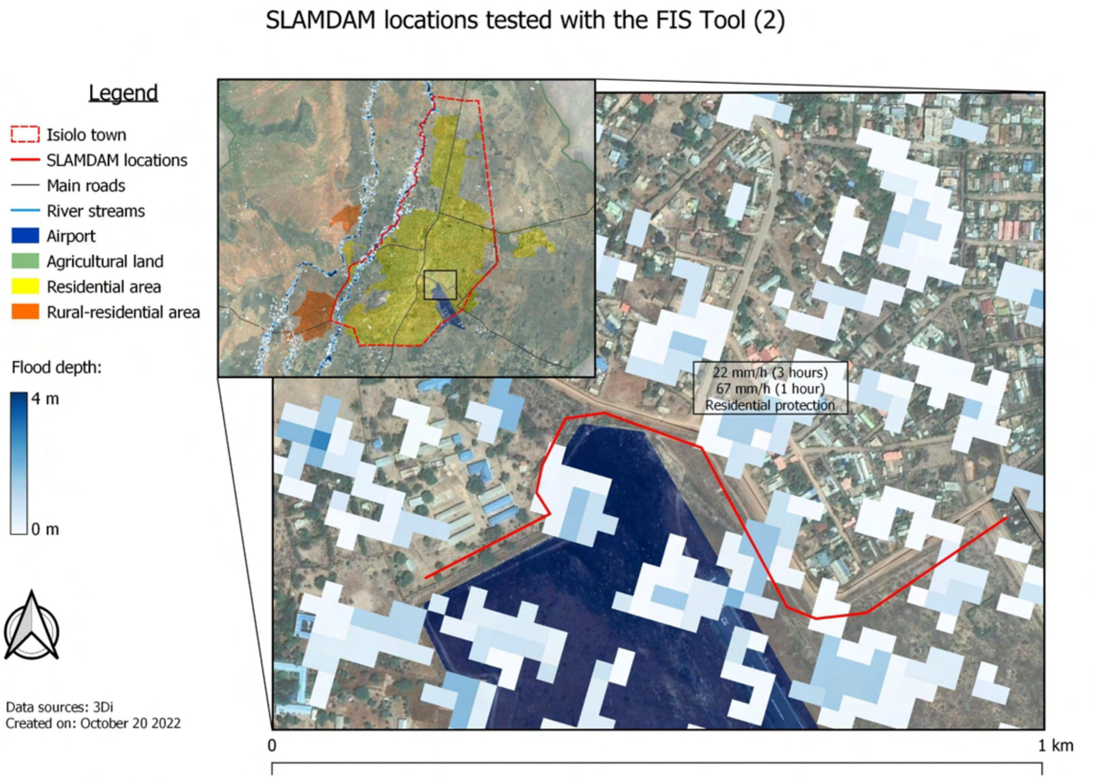


Figure 10.8: Possible locations for implementing the SLAMDAM based on FIS Tool simulations (2)

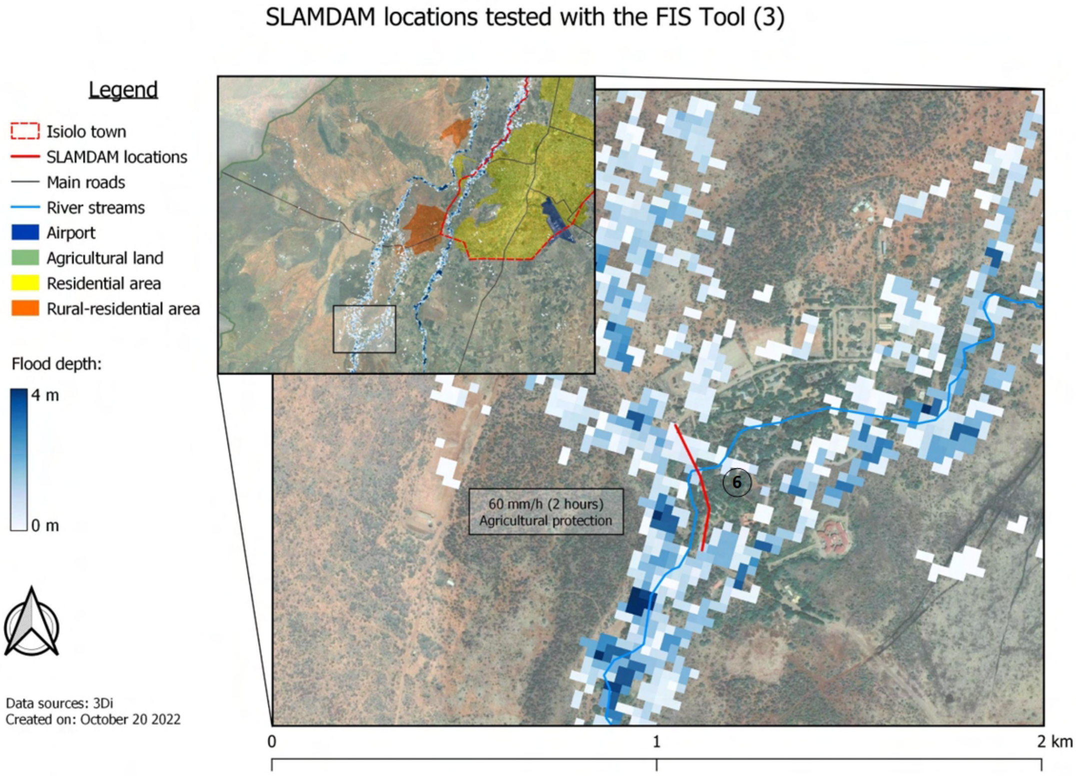


Figure 10.9: Possible locations for implementing the SLAMDAM based on FIS Tool simulations (3)

From the costs and benefits simulations, six possible locations for the deployment of the SLAMDAM are selected. These locations are colored in red in the three figures above. Furthermore, the type of rain event, the depth of the flood water and the type of land that is protected are shown in the figures. The definition of the boundary conditions for the SLAMDAM together with the site investigation will provide an insight in whether the deployment is really possible on the designated locations based on the modelling. Section 10.4 will elaborate on the site investigation, but first the boundary conditions are discussed.

10.3 Boundary conditions

Besides the examination of the benefits of the deployment of SLAMDAM by using the FIS Tool, the effectiveness of the dam needs to be investigated. For this, the boundary conditions for the implementation of the SLAMDAM are defined (Figure 10.10).

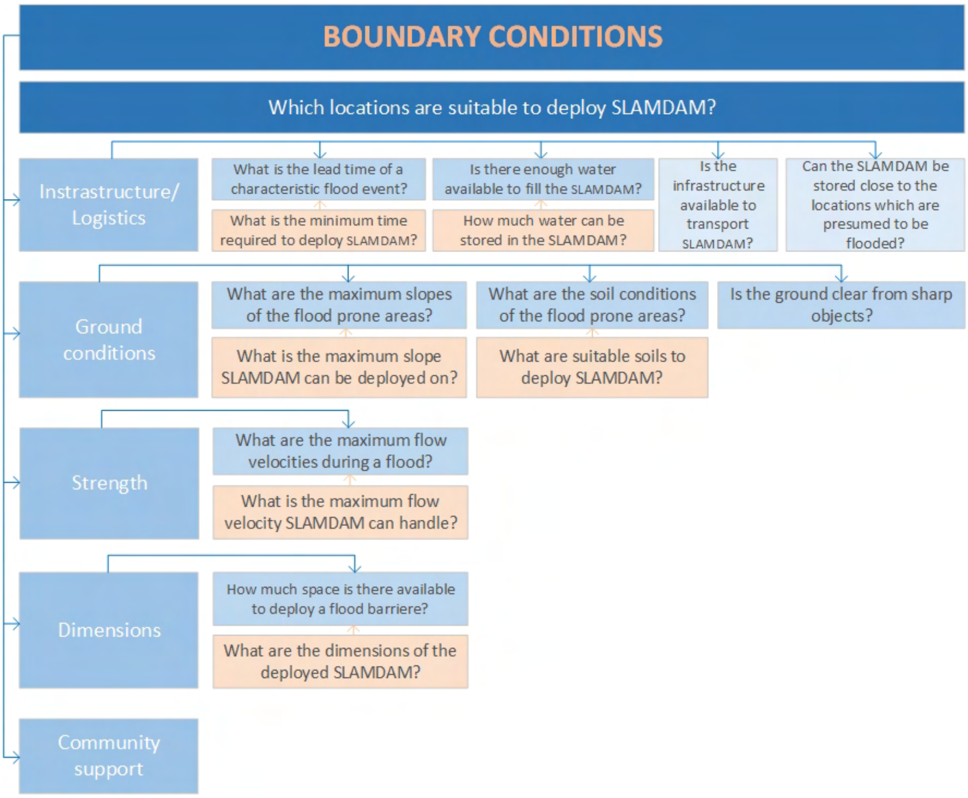


Figure 10.10: The boundary conditions for the deployment of SLAMDAM

There are certain criteria the deployment area has to agree to be suitable for the SLAMDAM. The features of the SLAMDAM affected of these criteria are colored in orange in the chart (Figure 10.10).

10.3.1 Infrastructure/ Logistics

The minimum time to deploy SLAMDAM depends on the span from the storage place to the deployment place. Therefore, the right infrastructure to transport the dam from place to place needs to be assured. Furthermore, the deployment time is dependent on the time required to get the SLAMDAM in place and fill it with water. This on its turn depends on the length needed to be protected and the amount of people that are available to fill the dam. It is recommended to use a water pump with at least capacity of 1200 L/min. As the SLAMDAM can store around 10,000 liter of water, one dam can be filled in around 8 minutes with this pump. That means that in an hour over 35 meters of the dam can be placed, provided that there is enough water available to fill the dams. Furthermore, it is required to know what the lead time of a characteristic flood event is to be able to know when to start the deployment of SLAMDAM and to know if the deployment is fast enough. Derived from the time it takes to fill 35 meters of dam, it can be stated that the SLAMDAM can safely be deployed if the lead time of the flood, counting from the moment the rain event starts until flooding occurs, is more than an hour.

3Di is used to calculate the lead time of the flood events from the different scenarios. This is shown in Table 10.9, the lead time is the time it takes after the start of a rain event to reach Isiolo Town. With the help of interviews conducted with the local community and with the WRUA, it became clear that an arrival time between 5 to 6 hours for a flood after the start of a rain event is to be expected. And with the mention of the WRA that the, now broken, early warning system would give a warning when a event of $60mm/h$ happened. Table 10.9 can be used to validate that the used Digital Elevation Model, land-use/land classification map,friction map , infiltration map, & interception files (chapter 7.7.1 & 7.7.3) are good to represent reality when it comes down to arrival time of floods after a rain event. From the table it can be seen that in all scenarios the arrival time of the flood is longer than one hour. That means there will be enough time to deploy the SLAMDAM in these situations. However, a proper early warning system should be in place.

Table 10.9: Lead time of different flood scenarios generated with 3Di

Storm [mm/h]	**Duration storm** [$hour$]	**Type of storm**	**River**	**Arrival time** [sec]	**Arrival time** [hours]
60	2	Interview	East-Marania	18600	5.167
60	2	Interview	West Marania	31400	8.722
90	1	Local Climate Change	East-Marania	19300	5.361
90	1	Local Climate Change	West Marania	43100	11.972
18	3	Whole Region	East-Marania	22300	6.194
18	3	Whole Region	West Marania	25800	7.167
30	3	Local Climate Change	East-Marania	26900	7.472
30	3	Local Climate Change	West Marania	no data	no data
23	3	Local Climate Change	East-Marania	36100	10.028
23	3	Local	West Marania	no data	no data
81	1	Local	East-Marania	21600	6
81	1	Local	West Marania	57100	15.861
55	1	Whole Region	East-Marania	10400	2.889
55	1	Whole Region	West Marania	12000	3.333
27	3	Local	East-Marania	29000	8.056
27	3	Local	West Marania	no data	no data

10.3.2 Ground conditions

Not all sites are suitable for the deployment of SLAMDAM. The suitability is depending on the soil type but also on the topographic gradient. If the slope is too steep, the SLAMDAM might loose its friction with the ground due to gravitational forces and gain momentum. To avoid this, it is recommended to deploy the SLAMDAM on fairly flat terrains. Additionally, the SLAMDAM is not very suitable to be deployed on sandy soils. A geohazard associated with sandy soils is internal erosion or soil piping (British Geological survey, n.d.). This happens when water that seeps through the soil carries with particles. Eventually, this can cause the the dam to move and form an hazardous situation. With 3Di and the FIS Tool locations for the possible deployment of SLAMDAM are selected (10.2.4). From these maps it cannot clearly be seen if the dam is placed on sandy soil, so this has to be verified with site investigations at these selected locations. Furthermore, the site needs to be clear from sharp objects to protect the dam against damage.

10.3.3 Strength

During a flood event, both hydrostatic and hydrodynamic forces act on the SLAMDAM as explained in section 6.2. The hydrodynamic forces will have influence on the robustness of the positioning of the SLAMDAM. The SLAMDAM will 'stay' on its place if the resultant force of the SLAMDAM is greater than the force of the flood water. This resultant force is determined by the friction coefficient with the ground together with the normal force of the SLAMDAM. Figure 10.11 shows the different forces acting on the dam.

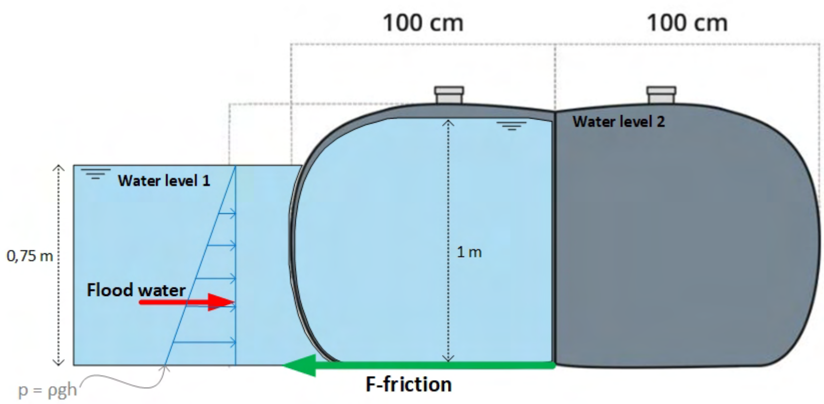


Figure 10.11: Schematization of forces acting on the SLAMDAM

First of all, it has to be realized that the water level of the flood event (water level 1) is lower than the water level in the SLAMDAM (water level 2). This is the case when the SLAMDAM is not overtopped (SLAMDAM

B.V., 2016). Due to this the the resulting force of the flood water lays below the centroid of the SLAMDAM. Secondly, the SLAMDAM has a concave shape, the shape secures that the force of the water is acting under an angle on the EPDM (SLAMDAM B.V., 2016). This force 'pushes' the SLAMDAM to the ground. The concave shape also ensures that the dam has no momentum and therefore stays on its place.

The second fundamental is the friction of the SLAMDAM with the surface. This friction results in a friction force which keeps the SLAMDAM in place. The friction coefficient depends on the interface between the surface on which the SLAMDAM is deployed and the EPDM material. To determine the stability of the dam, the force of the flood is compared with the resultant friction force of the dam. If the resultant friction force is higher than the force of the flood, the dam will stay in place. Different friction coefficients are compared in Table 10.10. Based on the study of Vaid and Rinne (1995) and Li, Yan, Xiao, Li, and Geng (2021) to geomembrane coefficients to interface friction, a range of μ [0.20 - 0.7] is taken. This is to test the stability of the SLAMDAM on both sandy and clayey soils. However, the exact friction coefficient between EPDM and the soil on which the SLAMDAM will be deployed, can only be experimentally determined.

Table 10.10: Stability of the SLAMDAM; Friction forces

Friction Coefficient [μ]	**Vsd** [m^3]	**Msd** [kg]	**F-friction** [kN]	**F-flood** [kN]	**delta-F** [kN]
0.20	10	10,000	19.62	18.39	1.23
0.25	10	10,000	24.53	18.39	6.14
0.30	10	10,000	29.43	18.39	11.04
0.40	10	10,000	39.24	18.39	20.85
0.50	10	10,000	49.05	18.39	30.66
0.60	10	10,000	58.86	18.39	40.47
0.70	10	10,000	68.67	18.39	50.28

The flood water force is calculated with the water pressure at a depth of 0.75 meter, as this is the height the Profidam L can retain. The water pressure is multiplied by the area of one compartment (length * height) to calculate the force acting on the dam and a water density of 1000 kg/m^3 is assumed. From Table 10.10 it can be seen that even with a friction coefficient of 0.2 the friction force would still be greater than the force of the flood. This means the dam would stay in place. Would the flood water reach a height of 1 m due to, for example, waves or overtopping, then the floodwater force would increase to 24.53 kN and the friction coefficient should not be lower than 0.25.

Beside the risk of sliding due to hydrostatical forces, sliding can also occur due to hydrodynamical forces of the flood water acting on the dam (Koppe & Brinkmann, 2010). For this, the maximum flow velocity during a flood needs to be known and has to be compared with the maximum flow velocity the SLAMDAM can handle. Table 10.11 gives an overview of the flow velocities for the different flood scenarios. The inner pixel stream velocity is the velocity of the water in the middle of the river and the outer pixel stream velocity gives the velocity of the outer pixel of the flood event computed with 3Di. For the SLAMDAM it is known that it can handle a flow velocity up till 1 m/s perpendicular to the dam (SLAMDAM B.V., 2016). It can be seen that the stream velocities at the outer pixel of the flood events are all below 1 m/s. This means the SLAMDAM can be placed safely at these locations. In reality the SLAMDAM will be placed somewhere between the the riverbed and outside pixel of the flood event. Therefore, the stream velocity on the SLAMDAM will between the highest and the lowest value given in Table 10.11. Besides this, the stream of the flood will not hit the dam perpendicular but at an angle. This will lead to lower values of the stream velocities.

Table 10.11: Maximal stream velocity of different flood scenarios generated with 3Di

Storm [mm/h]	**Duration** [$hour$]	**Type of Storm**	**River**	**Maximum Stream Velocity** Inner Pixel [m/s]	**Maximum Stream Velocity** Outer Pixel [m/s]
60	2	Interview	East-Marania	2.82	0.78
60	2	Interview	West Marania	2.07	0.57
90	1	Local Climate Change	East-Marania	2.48	0.84
90	1	Local Climate Change	West Marania	1.94	0.56
18	3	Whole Region	East-Marania	1.30	0.54
18	3	Whole Region	West Marania	0.67	0.578
30	3	Local Climate Change	East-Marania	2.09	0.48
30	3	Local Climate Change	West Marania	no data	no data
23	3	Local Climate Change	East-Marania	1.09	0.43
23	3	Local	West Marania	no data	no data
81	1	Local	East-Marania	1.62	0.62
81	1	Local	West Marania	0.40	0.28
55	1	Whole Region	East-Marania	1.95	0.43
55	1	Whole Region	West Marania	1.80	0.33
27	3	Local	East-Marania	1.16	0.54
27	3	Local	West Marania	no data	no data

10.3.4 Dimensions

The SLAMDAM now available on the market has a maximum height of 1 m and can retain up to 75 cm. Depending on the height of the flood and the space that is available in the flood area, it can be chosen whether or not a SLAMDAM is a suitable mitigation measure. In section 10.2.4 the maps with possible locations for implementing the SLAMDAM are shown. From the figures it can be seen that the flood water has a depth between 1 and 4 m. At location 1 and 2 it is therefore recommended to place the SLAMDAM more land inwards to make sure the SLAMDAM is not overtopped in order to hold its protecting function.

10.3.5 Community support

Another important aspect for the deployment of the SLAMDAM is community support. As the floods affect the agricultural or residential area of the local people, they will be the people benefiting from the dam. Therefore, it is important that the local community is informed about the technology so that they can deploy it in case of flooding. They would also know best where and when then deploy the dam as it is their land. If the community is aware the benefits of the dam, it is also less likely that they will vandalise it. Hence, the community should be involved from the start of the project. During this project, awareness along the local community is generated by organising two demonstration days. Different compartments of the SLAMDAM were shown and filled with water. The main objective of these days was to generate awareness of the dam along the community and other involved parties. The general reception of the community was very positive. In the news article in the Nation, of which the link is provided in Appendix J, this is confirmed by a farmer David Mwiti Nabea who states that the county government should adopt the technology to manage floods in Isiolo Town (Wairimu, 2022).

10.4 Site investigation

In section 10.2.4 the possible locations for implementing the SLAMDAM are shown. With a site investigation it is verified if these locations are suitable for deployment of the dam. Because of limited amount of time, only the first four locations are visited.

Location 1

Location 1 is lays next to the East-Marania river. Depending on whether the focus is on protecting residential area or agricultural land, the SLAMDAM can be deployed on either the left or right side of this river (Figure 10.12a). From the site investigation a mosque and greenhouse were found to be located on the left side of the river. These could be seen as high-value properties which should be protected against floods.

(a) Land use around the river bed

(b) Overview of the river

Figure 10.12: Site investigation of location 1 (1)

It can be seen that the right side of the river (Figure 10.13a) is fairly flat which makes it a suitable location. The left side, however, should first be cleared from sharp rocks before deployment of the SLAMDAM is possible (Figure 10.13b).

(a) Right side of the river bed

(b) Left side of the river bed

Figure 10.13: Site investigation of location 1 (2)

From the width of the bridge, which is about 7 meters, it can be deducted that the water can rise to quite an extend. This can be confirmed with the flood maps created with 3Di (section 10.2.4). It is therefore very likely that in case of a flood event there is enough water available to fill the SLAMDAM. It is, however, recommended to place the dam a little further away from the riverbed to prevent overtopping. Nonetheless, the topographic and ground conditions are suitable for the deployment of the dam.

Location 2

Location 2 is slightly more south than location 1 and is also along the East-Marania river. Agricultural land is located on both the left and right side of the river (Figure 10.14a). Here, watermelons and bananas are grown and the water from the river is used for irrigation. The land around the river bed is suitable for the deployment of the SLAMDAM, as the terrain is flat and without sharp stones or other objects. From the size of the bridge it can be assumed there will be enough water to fill the dam. An additional advantage of the SLAMDAM in this area could be the water storage for irrigation purposes.

(a) Land use around the river bed (b) Width of the bridge

Figure 10.14: Site investigation of location 2

Location 3

A little bit further upstream of the East-Marania river, location 3 is positioned. From the Figure 10.15 it can be seen that the sides of the river are covered with vegetation and trees. This makes it not a very suitable location for the deployment of the SLAMDAM.

Figure 10.15: Site investigation of location 3

Location 4

Location 4 is positioned on the West-Marania river. This location is chosen for the protection of residential area (section 10.2.4). From the site investigation it can be seen that the riverbed is very steep and the residential area is located far away from the river (Figure 10.16a and 10.17a). Because of this topographic gradient, the SLAMDAM would not be a suitable flood mitigation measure at this location and it is possibly not even necessary because the water has much space to flow before overtopping of the river beds would occur and before it would reach residential area.

(a) Land use around the river bed (b) Overview of the river

Figure 10.16: Site investigation of location 4 (1)

(a) Height of the riverside (b) Water eroded stones in the riverbed

Figure 10.17: Site investigation of location 4 (2)

10.5 Risks

From the SLAMDAM demonstration and pilot projects in the past a lot has been learned. Some of the challenges that arised during this project are listed in the Table 10.12 below.

Table 10.12: Risks associated the deployment of the SLAMDAM

Risk	Description
Water quality	To fill the SLAMDAM, floodwater from the river is used. The water can get slimy in the dam while stored due to the material of the dam. If this water is then later used for irrigation, its quality is not known.
Overfilling	Because there is no system in place to show that the dam is full, the dam can easily be over- or underfilled. This can cause the dam to underachieve.
Vandalism	The SLAMDAM is made of a plastic material (EPDM), therefore it is venerable for vandalism. People that are not aware of the purpose of the dam, might try to steal the material or damage it.
Backwater	The SLAMDAM forms a barrier for flood water that would normally overflow on the land. The risk arises that, due to the barrier, more water is directed towards downstream than normally, so this could possibly transfer the risk of flooding to downstream areas.
Organisation	Because the dam is used by the whole community, it has to be clear who owns the dam and who is responsible. So that in the case of floods the dam can be deployed rapidly.

The following chapter will compare the SLAMDAM to other possible flood mitigation measures.

Chapter 11

Other mitigation measures

Section 6.5 has discussed several other mitigation measures besides the SLAMDAM. Most possible measures have been evaluated in the Integrated Flood Management Plan 2013 for the Isiolo River Basin. From these mitigation measures which are likely to be effective in the Isiolo River Basin some have been chosen to compare with the SLAMDAM. To do this, this chapter first explains the the criteria on which the mitigation measures will be evaluated on. In the second section all previously mentioned mitigation measures will be directly compared with the SLAMDAM to give a overview on each advantages and disadvantages over each other. In the third section the mitigation measures which can also be implemented in the FIS Tool will be shown. After this the ranking of the mitigation measures is shown.

11.1 Criteria for evaluation of mitigation measures

To assess the performance of the SLAMDAM with respect to other mitigation measures and compare them to one another, a scoring matrix has been formulated as seen in Table 11.3.

The selected criteria are based on the framework by the Organization for Economic Cooperation and Development (OECD)(Organization for Economic Cooperation and Development, 1992). Initially consisting of five criteria, it currently defines six base criteria for the evaluation of development projects in the international stage. The Development Assistance Committee has since its first publication updated the framework after critiques highlighting the values it did not cater for (Organization for Economic Cooperation and Development, 2021). The DAC evaluation methodology is to the present day the most used reference for international development projects, hence the use of this framework as inspiration for the evaluation of flood mitigation measures in the Isiolo River Basin. The six defined criteria defined by the DAC are subdivided in the themes: relevance, coherence, effectiveness, efficiency, impact, and sustainability (Organization for Economic Cooperation and Development, 2021). Putting the framework in the perspective of this project, five criteria have been selected as main themes for evaluation, of which each is divided into separate categories. The DAC criteria serve as a blueprint to build upon the Isiolo project and therefore has been adjusted to best match the scope of the research. Besides the DAC criteria, works by de la Concha (2020) and Chianca (2008) which critique the current formulation of definitions by the DAC, have aided in formulating a fit for purpose set of definitions. The five criteria used to determine the added value of each flood mitigation measure are explained below.

Relevance
The mitigation measure must tackle the main problem at hand, namely, reducing or preventing flood risk. Furthermore, the benefits provided by the mitigation measure should focus on the goals and priorities of the local authorities as well as the needs of the population affected by the mitigation measure. This criterion is scored based on the following three sub criteria:

- Sensitive to situation: Does the mitigation measure have as its main purpose the reduction or prevention of flood risks?
- Partner/ institution (as defined by the Organization for Economic Cooperation and Development (2021)): Does the mitigation measure match the goals and priorities of the local authorities and any involved organisations or institutions?
- Beneficiaries: Does the mitigation measure cater to the needs of the population affected by the mitigation measure?

Effectiveness

Next to having flood mitigation as its main objective, the measure must actually be able to achieve this objective. The results it provides have to be noticeable, and any difference in results between different groups should be assessed. Effectiveness is scored based on the following sub criteria:

- Results (floods): Does the mitigation measure achieve significant results in tackling the problem of flooding?
- Results (other): Does the mitigation measure achieve significant results in tackling other environmental problems enhanced by climate change? (e.g., drought, water quality, temperature increase)
- Added benefits: Does the mitigation measure achieve significant results in tackling non-environmental problems? (e.g., economic, social, cultural)

Sustainability

It is desirable for interventions and solutions to be effective a considerable amount of time, and that its implementation does not just delay or push forward the main problem. In order for a mitigation measure to last, the implementation of such should be sustainable on various aspects. It is important to look at how well the measure has performed in the past as well with regard to sustainability. The sustainability of a mitigation measure is scored on the following sub criteria:

- Environmental: Does the measure require disruption of the local environment and how much? What is the effect on its surroundings after the flood event?
- Financial (maintenance): Does the measure require high maintenance costs to keep it operational?
- Technological: Is the measure up to standard with regard to technology while comparing it to similar alternatives? Does it pose the risk to become “old-fashioned” in the near future?
- Institutional/ social: Is the measure well-received by the local community as well as political entities? Is society capable to continue implementing the measure in terms of their own values and beliefs?

Efficiency

One of the main limiting factors of big development projects and interventions are the costs. Preferably, solutions should provide the highest possible benefits (e.g., highest reduction of flood damages) with the lowest possible cost. The results from the FIS Tool will aid in scoring the benefits and costs of each mitigation measure. Furthermore, a timely preparation of an intervention is preferred. However, when looking at flood events, the amount of preparation time is limited by the forecast of the event. Efficiency is scored based on two sub criteria:

- Cost-effectiveness: What is the amount of cost (monetary and non-monetary) compared to the amount of benefits (monetary and non-monetary) the measure provides?
- Time-effectiveness: What is the time required to provide significant results and is it possible to implement the mitigation measure on short notice?

Impact

Flood mitigation measures unfortunately do not bring positive effects to all of its surrounding population. Some of them may even generate unintended negative effects, which in retrospect have not been accounted for. It is important for flood mitigation measures to have far extended reaches, instead of providing heavily localized solutions. Furthermore, there are long-term positive or negative effects which can come from an intervention (e.g., economic, social, cultural, etc.). The last two sub criteria which the mitigation measures will be scored on are as follows:

- Extent: What are the higher-level effects the measure is expected to provide and how far (spatially) does it reach?
- Long-term: What are some of the long-term positive or negative effects that come as a result of implementing the mitigation measure?

11.2 Comparison SLAMDAM with other measures

Each mitigation measure is different and has its own functions. This causes that it is not easy to compare mitigation measures with one another. The mitigation measures mentioned in chapter 6.5 all have as their main function to reduce or prevent flood risks, but they do not have the same manner to prevent floods. In section 11.4 of this chapter, the measures will be evaluated in a matrix according to the criteria from section 11.1. Because the goal of the research is to compare the mitigation measures with the SLAMDAM, it has been chosen to first highlight some differences between the SLAMDAM and the other mitigation measures. Below the mitigation measures will be, as far as possible, compared with the SLAMDAM. The mitigation measures have been divided in different subgroups for a clearer overview, these categories are: emergency measures, infiltration measures, and structural measures.

11.2.1 Comparison with other emergency measures

One of SLAMDAM its main purposes is that it can be used as an emergency measure in response to sudden rainfall induced floods. From the other mitigation measures, the sandbags, a Flood Early Warning System (FEWS) and the flood hazard map are mitigation measures that can also be used during emergencies.

Sandbags

Sandbags and the SLAMDAM are very alike. Both can be deployed just before a flood and can be removed afterwards without having used permanent infrastructure. Their main differences are in the way they are used/constructed and their failing mechanisms. For the construction part, the most important difference is the speed of implementing both measures. One SLAMDAM can be rolled out and filled in a matter of minutes: 100 meter of SLAMDAM can be rolled out in approximately 1 hour by just 2 persons (SLAMDAM B.V., 2016). The sandbag on the other hand not only takes more time to built, it also needs to be laid out carefully per sandbag and per row to be sure that there is no leakage of water coming through the sandbags. This could still be done with 2 persons, but more persons to carry the bags would be advised as for a comparison one would need 1300 sandbags to built a dike similar to 1 SLAMDAM unit (Peterborough, n.d.). Another related aspect to required manpower and time is the way of filling the measure. All the sandbags need to be filled with sand and need to be brought to the desired location. A SLAMDAM does also need help to be filled because it would need a pump and hoses connecting the pump to the SLAMDAM to fill it with available water, but this still will be faster then a sandbag dike and it requires way less manpower. Both need resources, but the sandbags would need more preparation time to increase the implementation speed.

Another difference is that the sandbag has different failing mechanics as explained in chapter 6.5. These were: overflow, sliding, rotation, and seepage. The SLAMDAM does also has overflow as an failing mechanism but it does not slide or rotate due to the flexibility and weight of the dam provided that the SLAMDAM is used on not too steep slopes. The SLAMDAM can also be prone to seepage but since it is a flexible dike it can withstand seeping longer. If piping is successful on an sandy soil then the sandbag will fail sooner.

Flood early warning system (FEWS)

A Flood Early Warning System is also a emergency measure even though it needs to be constructed before the emergency occurs. Comparing a temporary dike to a system giving warnings of floods is (almost) impossible. Both systems differ severely in the way of impact. A FEWS can warn people in a big extent, which could save more lives compared to the use of the SLAMDAM, provided that the community knows how to respond to the alarm. Another advantage of the FEWS is that it can gather data which can be used for future floods. However, the water is not hold back so much damage can still be done, unless the alarm results in deployment of other emergency measures which do withhold the water. On the other hand, the SLAMDAM actively protects against floods and the water is hold back effectively. Therefore, much damage is prevented but more locally where the dam is deployed.

Flood Hazard map

Just like a FEWS, a flood hazard map is hard to compare to a SLAMDAM, because this is also a passive measure which does not withhold the water. With the hazard maps, the authorities and people can clearly see where floods are likely to happen. For each different scenario of a rain event it is possible to make a flood map. This mapping can help in future urban planning. Compared with the SLAMDAM the biggest difference would be that for the SLAMDAM there is no need for highly technically trained persons to use it. Whereas for a map one would need a highly detailed hydrodynamic model and experts in hydrology to make these maps. The maps can also get outdated if surroundings like land cover and land use change. For this reason, the maps need to be updated regularly, whereas the SLAMDAM can be used its whole lifetime when the boundary conditions like proper soil and slope are set. The measures could however also be used together. The hazard map can pinpoint where flooding is likely and has a severe impact. These areas could be protected by the SLAMDAM.

11.2.2 Comparison with infiltration measures

Infiltration measures are different than the SLAMDAM, because they will let water in and let the water infiltrate or use it for different purposes. The SLAMDAM has one of its extra benefits that it can also retain water within the dam itself.

Infiltration areas

Under infiltration areas a lot of different types of solutions exist as explained in chapter 6.5.4. The main comparison these solutions have with the SLAMDAM is that they all have the capability to retain water. For SLAMDAM this water can be reused for agricultural purposes or as drinking water for cattle or as water for washing. For infiltration areas the difference is that the water that infiltrates can not directly be reused. The water will be used by vegetation to grow or the water can infiltrate deeper in the ground where it can potentially recharge groundwater. Either way, the water cannot be directly used for human activity whereas for the SLAMDAM it can. But one extra benefit and difference compared to the SLAMDAM is that infiltration areas could create a cooler environment if it creates a higher albedo since this results in more reflected sunlight (Taha, Akbari, Rosenfeld, & Huang, 1988). One thing that is not beneficial from the infiltration areas is that it could become saturated, meaning that no water can infiltrate anymore and on that area floods will not be prevented anymore. A SLAMDAM could potentially be as long as possible and retain as much water as one would need.

Forestation

Forestation is quite similar to an infiltration area, however it has a slightly bigger extent to prevents floods. Forestation, if implemented on wide scale, cannot only prevent flooding due to infiltration and interception of rainfall, it can also cause more friction which causes slower overland flow and less accumulated flash floods. Comparisons between the SLAMDAM and the forestation lies mostly in preventing of flooding. Compared to the SLAMDAM which actively blocks the water from overflowing, trees are not very effective in preventing flooding separate from the more friction it causes which slows down the velocity of the water stream. Another downside of forestation is that it takes very long to implement this measure and if trees or vegetation break or die due to heavy floods it will take a very long time to re-implement the measure because it takes time for the trees to grow. On the other hand, the SLAMDAM is a temporary structure which can be deployed with high speed and it is not prone to damages. Also, it protects better against flooding. However, forestation is accompanied by more added benefits: for example the biodiversity increases, the area becomes greener and can attract more tourism, and the water gets purified. Interestingly, there can also be a way that the two work together. The water from the SLAMDAM can be used to water the trees for forestation in times of drought.

11.2.3 Comparison with structural measures

Structural measures are measures that need to be constructed and cannot be easily removed. To do this it should be demolished. But because it is permanent, the measures are always mitigating the risk of flooding, even when the flooding is unexpected. Because SLAMDAM is a temporary structure this characteristic is the main difference between the measures in this paragraph and this difference will not be addressed again but must be kept in mind as big difference. Structural solutions include: retarding basin, excavation or widening of the river bed, and the development of drainage system.

Development of drainage systems

The development of drainage systems as already addressed in section 6.5 needs to be done if the current system is outdated or not well maintained. Because the population of Isiolo Town is and has been growing (5) this has become a problem. If the system would be developed this would reduce urban inundation. The main comparison between the development of drainage systems with the SLAMDAM is that the development of drainage system can also cause a higher flow capacity. For the SLAMDAM the height of the river is increased and for the development of drainage system it can be chosen what to adjust and the water can be directed away from the city. So with both measures the cross-section can be increased, resulting in less risk of flooding. Differences mainly include that the development of the drainage system demands continuous maintenance whereas the SLAMDAM does not need a lot of maintenance.

Excavation or widening of the river bed

Excavation or widening of the river bed is a structural measure which causes a bigger cross-section for the water to flow through. Just like a SLAMDAM (which can heighten the banks) this means less water will overflow from the river. The main disadvantage and difference from excavating a river would mean that a lot of construction needs to be done to deliver this bigger cross-section. Land, possibly of farmers or residential areas, needs to be removed and this includes removing of vegetation, Also, the measure needs to be maintained to keep the cross-section needed because erosion leads to a lower cross-section again after a while. In contrast, a SLAMDAM is only a temporarily measure which does not change the environment or someones land. However the excavation of a river could mean way bigger cross-sections can be created, potentially being more effective against flooding.

Retarding Basin or Pond

A retarding basin is an area where water can be stored if the capacity of a river cannot sustain the amount of water or if there is a very high amount of overland runoff. This basin needs to be digged in a certain area or dikes needs to be built to create a buffer zone where the water can be retained. Just like a SLAMDAM water will be stored in this mitigation measure and can be used in a later stage. The water could also be directed back to the river system when there is enough space again. A demerit is that the basin has a maximum capacity, whereas the SLAMDAM potentially has infinite storage, provided that space, units and, labor force are present. Another difference is that the water in a retarding basin can become in contact with the environment. This causes more mosquitoes, chance for bacterial growth, and vaporization of the water. In contrast, the SLAMDAM is vapor tight and due to the black exterior the water inside can reach a high temperature which is not favorable for bacterial growth.

11.3 SLAMDAM versus other mitigation measures using 3Di and FIS Tool

The FIS Tool is able to compute the benefit of flood mitigation measures in a specified region. For the case of Isiolo Town, it is possible to compute the benefits of other mitigation measures than the SLAMDAM, such as the retarding basin and the infiltration areas. This section will explain in detail how these mitigation measures have been assessed with the help of 3Di and the FIS Tool.

Retarding Basin in Isiolo Airport

The retarding basin in Isiolo Airport, assessed by Republic of Kenya (2013), is expected to greatly reduce flood damages within Isiolo Town. As mentioned before, one of the three biggest factors of flooding in Isiolo Town is the extra runoff created by the construction of Isiolo Airport. The retarding basin is modelled in 3Di by introducing an area with an infinitely high infiltration rate, with a maximum infiltration capacity of 1 meter. The following image gives a visual representation on what it looks like to model a retarding basin in 3Di:

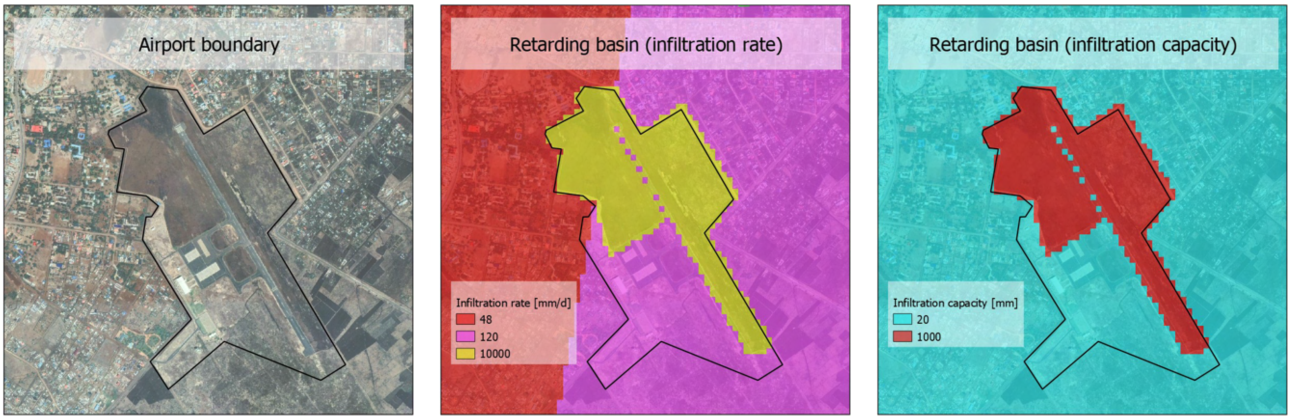


Figure 11.1: Model parameters in 3Di for modelling a retarding basin in Isiolo Airport

The model is afterwards run twice in 3Di; once without the modified infiltration rate and infiltration capacity layers, and once with the modified layers. This is to compare the result of the flood map with the mitigation measure to a scenario with no mitigation measures. Besides the infiltration capacity and infiltration rate layers, all the other parameters have to remain the same. Therefore, both simulations were run with a rain event of 60 mm/h with a duration of 2 hours. The total simulation time of both schematisations was equal to 17 hours and 39 minutes, the corresponding flood maps can be seen in Appendix N. After uploading the flood maps into the FIS Tool, an estimation of the total damages is computed. The difference in damages between the default scenario and the scenario with the mitigation measure becomes the benefit of implementing the mitigation measure, which is shown in Table 11.1.

Table 11.1: Benefits of Retarding basin at Isiolo Airport (from FIS Tool), from a 60 mm/h storm (t= 2 hours)

Topic	Benefit
Residential damage	567782,- €
Agriculture damage	-130,- €
Affected number of people	199
Affected residential area	44800 m^2
Affected agriculture area	-4800 m^2

Infiltration Area in Isiolo Town

MetaMeta (2022) proposes the implementation of a 'Sponge Basin' or 'Sponge City' within Isiolo Town, which can have various environmental, social, and cultural benefits. When looking into flood mitigation, the main benefits are an increased storage in the subsurface as well as an increased infiltration capacity. The result of this is a reduction of the peak flows from the flood downstream of the Sponge Basin. In 3Di, one can model the effects on the flood map by introducing an infiltration area with a higher infiltration capacity and infiltration rate. The model schematisation for an infiltration area in 3Di looks as follows:

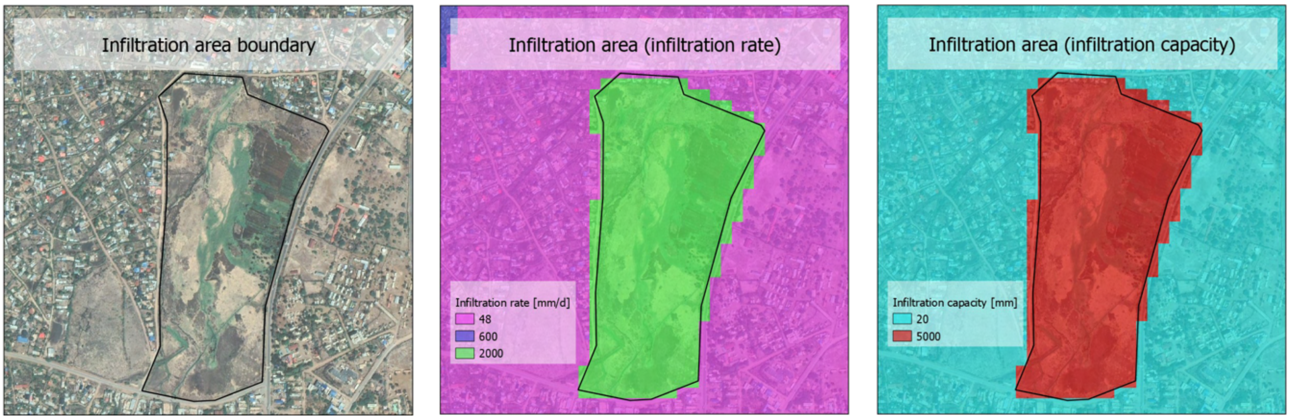


Figure 11.2: Model parameters in 3Di for modelling an Infiltration area in Isiolo Town

Just as with the retarding basin at the airport, the model is run twice in 3Di. The default schematisation remains the same, and the second schematisation contains the infiltration area modelled in 3Di. The resulting flood maps can be seen in Appendix N. The same precipitation event and run time are used as the previous mitigation measure: a 60 mm/h event for 2 hours and a simulation time of 17 hours and 39 minutes. After uploading the flood maps into the FIS Tool, the benefit of the mitigation measure is computed, and is shown in Table 11.2.

Table 11.2: Benefits of Infiltration area in Isiolo Town (from FIS Tool), from a 60 mm/h storm (t= 2 hours)

Topic	Benefit
Residential damage	75550,- €
Agriculture damage	-188,- €
Affected number of people	20
Affected residential area	9600 m^2
Affected agriculture area	-12800 m^2

Comparison mitigation measures to SLAMDAM

As can be concluded from the previous section, the retarding basin provides higher benefits than the infiltration area in Isiolo Town. This is only considering benefits with regard to flood risk mitigation. Other benefits of the mitigation measures (e.g., social, economical, environmental) are not included in the final assessment provided by the FIS Tool. Section 11.4 takes various aspects into account and scores every mitigation measure on the aforementioned criteria that have been formulated. Looking purely at flood damages however, it is noticeable that implementing both mitigation measures result in increased damages in agriculture. The question lies whether the higher residential protection outweighs the added damage in agricultural areas. The results provided in section 10.2, give an estimation of the benefit per meter of SLAMDAM. If the cost per meter of

SLAMDAM is known, then the other mitigation measures can be expressed as well in added benefit per invested money. Since both the retarding basin and infiltration area in Isiolo are projects which have not yet been realised and evaluated thoroughly, it is difficult to provide an estimation of the total costs per project. This complicates the comparison of the benefits, since the benefits from the FIS Tool presented in the tables do not include the made costs for implementation of the measures. However, an estimation of the costs will be given now.

Cost estimation mitigation measures

Each unit of 5 meters SLAMDAM that is 1 meter high costs approximately €2300,- , which means a cost of €460,- per meter of SLAMDAM deployed (this is disregarding the cost of the pump and fuel for the pump assuming this is included in the purchase of a SLAMDAM). The lowest benefit per meter SLAMDAM from the analyzed rain events is equal to €238.19 (see section 10.2). To get a return of initial investment on the SLAMDAM, the SLAMDAM must be deployed at least twice in any of the proposed locations, taking into account the assumed rain events (€238.19 * 2 > € 460). The longer and more often the same SLAMDAM is used, the more "profitable" the SLAMDAM becomes, meaning the prevented damages which would have occurred whilst not using the SLAMDAM are the profit of the mitigation measure.

The retarding basin in Isiolo Airport would have a total area of 525,430 m^2, as modelled in 3Di. For a retention basin of 1.5 metres depth, where the freeboard is around 0.5 metres, research by (Ellis, Biessan, O'Donnell, Vasconcelos, & Bowers, 2021) estimates the cost to be approximately €16.45/m^2. For the retarding basin in Isiolo Airport, this would mean that the initial investment costs are 525430 m^2 * €16.45 / m^2 = €8,643,323.5. The benefit of the mitigation measure for a rain event of 60 mm/h for 2 hours amounts to €567,782.-. This would mean that to get a return of initial investment there need to be at least (8643323.5/567782 = 15.2) 16 rain events of 60 mm/h for 2 hours. It is important to keep in mind that the cost takes labor costs in the United States into account. The lower labor costs in Kenya could drive the price down yet it is debatable whether it will have a significant effect in reducing the amount of rain events require to get a return of investment.

Case studies by Grey, Sorem, Alexander, and Boon (2013) show that high infiltration basin systems cost €204.52 / m^2 in the lowest price estimation. The surface area of the proposed infiltration basin by MetaMeta (2022) is approximately 267,380 m^2. This means a total cost of €54,684,557.60. With the benefit of €75,550.- after a rain event of 60 mm/h with a duration of 2 hours, the return of investment would be met after ($54,684,557.60/75,550 = 723.8$) 724 rain events. Just like the retarding basin, the costs of the mitigation measure are calculated with labor costs of the United States.

Assuming the costs of the mitigation measure can be divisible by the difference in average labor costs between the United States and Kenya, a more realistic approximation of the required number of storms to get a return of investment can be derived. According to Nation Master (2014), the average labor costs or disposable monthly salary after tax is 6.8 times higher in the United States than in Kenya. This would mean that there will be a return of investment for a retarding basin and an infiltration area after 3 (15.2/6.8 = 2.2) and (723.8/6.8 = 106.4) 107 rain events of 60 mm/h for 2 hours.

As can be derived from the previous calculations, the SLAMDAM performs best in flood mitigation when purely focusing on the mitigated flood damages per investment. A retarding basin in the Isiolo Airport comes at a close second, meanwhile the infiltration basin does not perform as well in returning the initial investment in the form of flood damages prevented. For the infiltration area it is unclear whether the monetary benefit will result in a return on investment due to the lower benefit of residential damage as shown in Table 11.2. The costs per mitigation measure should be known to properly compare the measures, this initial calculation is to provide a qualitative comparison of the performances as indication.

11.4 Ranking flood mitigation measures

With the criteria explained in chapter 11.1 it is now possible to fill in the scoring matrix and see how each mitigation measure would suit in the Isiolo River Basin. The results of the differences in benefit known from the FIS Tool in chapter 10 and section 11.3 which assesses two other measures than the SLAMDAM with the FIS Tool will be used for this evaluation. The discussed differences and comparisons between the mitigation measures will also be used when rating the measures.

Each (sub)category can be scored with a 0, 1, 2 or 3. A zero would mean that the mitigation measure scores very bad and therefore no points a given to the mitigation measure. For example if a mitigation measure has a disproportional high maintenance cost this would result in a 0 for that subcategory. A three will be given if a mitigation measure scores very high/good for that category. A mitigation measure that would almost certainly result in no floods could score a 3 in "Results (floods)". A one is given if a mitigation measure score low/bad on a category, so is mitigation measure has just one "benefit" extra next to preventing floods such as creating awareness then it would score a 1 in that category. A two is given when a measure scores medium/okay. This would mean for example if a mitigation measure does almost not negatively affect the "environment" but still has a bit of a influence on it, then it scores a 2.

Below in Table 11.3 the results of the rating per category are given.

Table 11.3: Scoring Matrix Mitigation Measures

	Relevance			Effectiveness			Sustainability				Efficiency		Impact			
	Sensitive to situation	Partner/ institution	Beneficiaries	Results (floods)	Results (other)	Added benefits	Environmental	Financial (maintenance)	Technological	Institutional/ social	Cost-effectiveness	Time- effectiveness	Extent	Long-term		
SLAMDAM	3	2	2	2	2	3	2	3	3	3	2	3	1	2	33	7.857
Development of drainage systems	3	3	3	3	1	2	3	1	2	3	2	1	2	2	31	7.381
Excavation or widening of river bed	3	1	1	3	1	0	1	0	1	1	1	1	2	2	18	4.286
Retarding Basin or Pond	2	2	2	2	2	1	1	2	2	2	1	2	2	2	25	5.952
Infiltration area	2	2	2	1	3	3	3	2	2	2	1	1	1	3	28	6.667
Sandbags	3	1	2	1	0	1	2	2	1	2	2	3	0	1	21	5.000
Forestation	1	3	3	1	3	3	3	3	2	3	2	0	1	3	31	7.381
Flood early warning system (FEWS)	2	3	2	1	0	2	3	1	2	2	3	3	3	2	29	6.905
Flood Hazard map	3	2	1	1	1	1	3	2	2	2	3	2	3	2	28	6.667
															Total points	Score

In Table 11.3 one can see that the SLAMDAM, the development of drainage systems, and forestation score the best in total amount of points. The mitigation measure with the least amount of points is the sandbag. An explanation per category will now be given to make some decisions clearer for some measures.

Sensitive to situation

In this category it is important that a measure has as main goal to reduce or prevent flood risks. This is why most of the flood mitigation measures score 3 points. However the forestation, infiltration area, and retarding basin score respectively a 1, 2 and 2 due to the fact that these mitigation measures do not have this as an main purpose. They focus more on infiltrating or collecting water and reducing the amount of water flowing through. A FEWS does reduce risks, especially in lives lost, but does not really prevent flooding itself.

Partner/ institution

Here it is important that a measure matches the goals and needs for local partners and institutions. The main reason most measures do not score a 3 is because one of the goals is that land is not taken away from local partners, but for most measures this would be the case. Next to this most needs of institutions were found to be related to drought issues as became clear after asking their main challenges. This results in a higher score for the water infiltrating or retaining measures.

Beneficiaries

For this category the effected population for each mitigation measure is taken into account if their needs are catered from the measure or not. Especially the excavation or widening of the river scores low as the most effected people would be those that have a loss of land and the land surrounding the rivers often contain agricultural lands. Also, many people live illegally in the riparian land as mentioned before, so their needs are not met as well because widening of the river would mean they have to move. Also the flood hazard map scores low because not many people of the community will benefit on a daily base from this measure but it is especially valuable for future urban planning of a town so for institutions who are engaged in this planning.

Results (floods)

For flood results the best measures are excavation or widening of the river bed and the development of the drainage system, both scoring a 3. Potentially these measures can cause no flooding at all if implemented in big extent. Most other measures score a 1 due to the fact they do have a limit in how much flooding they can hold or do not directly prevent flooding.

Results (other)

Other results focuses on tackling environmental problems (enhanced by climate change), think of droughts, water quality or temperature rises. A FEWS gets a 0 as it just gives warnings for floods but is not helpful in preventing other risks. Also a sandbag just prevents floods until a certain amount but does not provide extra results. Infiltration areas and forestation score a 3 because they also help in preventing temperature rises, droughts, recharging groundwater, increasing water quality, and reducing the sedimentation transport. Other measures score a 2 or 1 regarding the amount of extra results they give.

Added benefits

For added benefits the non-environmental benefits, cultural, political, and economical benefits are important. This is where for example the SLAMDAM, forestation, and the infiltration area score a 3. As there is more economical growth when water can be used for agriculture and more greenery causes more mental health (Nutsford, Pearson, & Kingham, 2013). Also, the SLAMDAM is an innovation which is related to development, so the SLAMDAM boosts other aspects than just flood protection as well. Measures that are already being used will be accepted more easily whereas an excavation or widening of the river would result in political and cultural setback as not only does it take away land, but with excavation politics should agree on this major operation as well, which is not easy in Kenya due to all the different small organisations.

Environmental

Environmental sustainability in this context means little to no disruption of the surrounding area where the mitigation measure is to be implemented. SLAMDAM requires no displacement of soil or big trees to be implemented. In some cases it might be necessary to remove plants or obstacles on the way, that is why it scores a 2. Excavation or widening of the river bed and retarding basins require heavy machinery to dig out land in order to give more room for water storage and they may constantly need digging out due to sedimentation from upstream regions. The measures which ranks the best are the non-structural measures, since they require no physical deposition of building materials or displacement of land.

Financial (maintenance)

For this category it is important to look at maintenance cost, the cost of building the measure is looked upon in the cost-effectiveness category. The excavation scores a 0 as this excavation would need to be maintained yearly and is very costly. A SLAMDAM is only a one-time purchase and could last at least 40 years. Forestation is also a 3, under the assumption that any damages can be overcome by nature itself. A FEWS gets a 1, although it could have been a 2 or 3, but in interviews with the local community it became clear that the old systems were an easy target for vandalism and broke if floods were to heavy, therefore it needs more maintenance or checks then one would expect. Development of drainage systems scores a 1 because continuous cleaning of culverts and drainage canals is necessary since many people are used to dispose their garbage in the drainage systems. However, it scores not a 0 because the costs of manpower to clean the culverts and canals is not as high as for example the cost to excavate the river bed with heavy machinery.

Technological

It is desirable to use the most innovative solutions, so that in the near future they do not get out competed by new innovations and require an upgrade. Besides excavation or widening of the river bed and laying down sandbags, all the solutions do not currently have alternatives which deem to be much more innovative, hence the relatively high score for technological sustainability. In the Isiolo River Basin, all of the mitigation measures being assessed are currently being implemented or considered as a good enough solution against flood risks.

Institutional/ social

Interventions require local support from both the government and the community in order to stay present. Excavation or widening of the river bed requires the displacement of surrounding population to create space for more water to flow. Despite proving to be very effective in mitigating flood risks, it can face a lot of backlash from the local owners of land, especially since floods are not frequently occurring in the Isiolo River Basin during the drought season. From interviews with local authorities and stakeholders it can be concluded that the SLAMDAM, forestation, and development of drainage systems are favored measures. These interventions which locals have shown interest in therefore receive a score of 3.

Cost-effectiveness

Only 2 mitigation measures score a 3, which are the FEWS and the flood hazard maps. They both are relatively inexpensive to built and are very effective in showing when a flood is to be expected or in showing where floods will end up. Both also could be used for future use in urban planning. The retarding basin, excavation, and infiltration areas cost relatively much which is the main reason they score a 1.

Time-effectiveness

Forestation scores a 0 in this category as it can take up multiple year before the vegetation has grown enough to reach its potential to reduce flood risks, although this is also depended on the type of vegetation. SLAMDAM, sandbags and the FEWS score a 3 as these can be almost implemented immediately. Only the shipping and setting up requires a bit of time. This score is a generally expected for all emergency measures. Only the flood hazard maps scores a 2 because the research takes time before the maps can be created and afterward it takes time for urban planning water management to create new plans taking these maps into account.

Extent

The most preferable interventions to a community as a whole are those which help the largest number of people. The extent of the different mitigation measures varies greatly. Sandbags are heavily localized and only protect an individual or a couple of individuals. SLAMDAM is required to consist of many units in order to protect a considerable amount of people or area. Infiltration areas also have a minimal reach, as can also be seen from the results in section 11.3. Forestation requires large planting activities along the whole river to impact a large group of people. FEWS and flood hazard map receive a high score due to the fact that they require cooperation and information between the whole catchment, and increasing the scale does not require much of a bigger investment or cooperation.

Long-term

Reducing flood risks in the long-term can create positive or negative effects to the community. These do not have to be directly linked to effects from less flooding, but higher order aspects such as community engagement, climate change awareness, and social equality are also possible. Forestation and infiltration areas help in the improving the ecological quality of the surrounding area. Due to the higher water content in the soil ecosystems can flourish. SLAMDAM, FEWS, and flood hazard maps raise awareness about the drought and flooding problems in the region, and require cooperation between multiple people. the increased communication between locals can increase social coherence and cooperation between individuals. Less flood risks in the long-term also results in a wealthier community, due to less economic loss due to storms. Therefore every flood mitigation measure provides positive higher order effects to some extent.

Chapter 12

Discussion and Recommendations

The conducted research has been accompanied by several limitations. These limitations will be addressed in this chapter. But despite these limitations, this report enables to provide recommendations for the used software and the feasibility of the SLAMDAM for future use or research.

12.1 Discussion

This report aimed to map the current flood risk mitigation measures in Kenya, and also specifically in the Isiolo River Basin. The literature study has provided much information about the current state of flooding and other related aspects. After gaining deeper insights in the current situation, the objective was to look into the feasibility of the SLAMDAM in the Isiolo River Basin by using the softwares 3Di and the FIS Tool provided and created by Nelen & Schuurmans. An assessment of other mitigation measures was performed in conjunction with the feasibility study of the SLAMDAM.

This procedure faced several limitations. First of all, for stakeholder mapping, many reports from relevant organisations are available but there have been many organisational changes in recent years partly due to the Water Act 2016 and shifts of departments between ministries. In addition, many reports and policy documents run until 2022, as this is an election year after which new policies will have to be made. Therefore, many of the used literature mention organisations that no longer exist and some bodies created in the Water Act 2016 such as the BWRC have not yet been formed. Also, a proposal was adopted in 2021 to merge three stakeholders (NDMA, NDOC and NDMU) into one: the National Disaster Management Authority. This is a crucial actor in flood risk mitigation and therefore it is hard that such an important organisation has not yet been formed. It is therefore not surprising that most of the challenges mentioned in the interviews are related to institutional issues. Another limitation is that on many government agency web pages important information is not available, or it is impossible to open certain web pages. In some cases, a website looks promising, but when clicking on the water department, for example, the page appears to be empty or documents are unavailable.

With regard to the stakeholders as well, it was difficult to arrange an appointment with some of the initially targeted contacts or it was hard to get into contact with them. Several attempts had been made to get into contact with some institutions, but unfortunately some never succeed to actually meet the right persons. This is probably due to people's busy schedules and the more traditional/hierarchical way of government protocols. In some instances, official letters needed to be sent out or permission by a higher power had to be given. Despite of this, for the limited amount of time assigned (8 weeks), there has been much contact with different parties and everyone was very co-operative. This enabled inside information and data, besides the publicly available online data.

Most of the other limitations and challenges during the project are related to the input of the tools. The input of 3Di influences the outcomes of the flood maps and therefore the input for the FIS Tool. These inputs depend on the available data sets.
Starting this research it became clear that a lot of data collecting needed to be done. To make a 3Di model for flood maps as accurate as possible the resolution sizes were recommended by Nelen & Schuurmans to be at least 30 by 30 meter or smaller. Next to this, data needed to be as new as possible to create a the most realistic models but recent data from local stakeholder were hard to gather and/or not available. And if available, the data was often not more accurate than global data or satellite data, although this would be expected of local data. So in general, the input data available for the 3Di model schematisation was of a relatively low resolution.

One of the least accurate data found is the data for land cover use. These maps were from 2015 and since land cover changes rapidly, these maps do not align with the present-day situation. Not only was this data

from 2015 and therefore 'outdated', it also has a low resolution of 310 by 310 meter. With the land cover data the friction map has been created which is implemented in 3Di. If a more up-to-date and especially a better resolution land cover data set would have been used, a better hydrodynamic model could have been created where water flows over land would have been more accurate.
Besides, the available digital elevation models have a resolution of 30 by 30 metres, and ideally a higher resolution is necessary to analyse smaller scale effects of overland flow. Next to that, the soil classification is outdated. Due to the short amount of time available for the project, it deemed difficult to obtain higher resolution and up-to-date data.

Another input for 3Di is the rainfall intensity. To come up with these rain intensities, rainfall data sets were required. The range of the data sets was unfortunately again quite limited and there is not much recent rainfall data available of the Isiolo River Basin. During the literature study it became clear that there used to be rainfall gauging stations within the basin, but after contacting the KMD it turned out that there is no more recent data available. This is because the gauging stations are not operational anymore for at least the past 10 years. Therefore, this report has used the rainfall data gathered by the KMD for the JICA project, of the period 1957-1988. This data is outdated and this complicates accurate calculation of the most recent daily rainfall for different return periods. However, since the period of data is quite extensive, it does provide a good indication.

Next to this, a connected limitation with gaining data from the organisation in charge of rainfall data, was the time it consumed. Contact was established via e-mail in the first week, but after a while it became clear that the official procedure for requesting data was needed. The required formal letter was handed in quickly after this response, but the response to this official request came a few weeks later. If the project would have lasted longer this would not have been considered a problem, but since the project only has a duration of 8 weeks the response came in already the last week of the project and calculations were already performed based on the more outdated data set. But since the answer was that there are currently no operating rainfall stations anymore in the basin, the outcome of the research did not change. Next to the use of the data set from the JICA team, the calculations also used data from the TAHMO. This is more recent daily rainfall data from the past 5 years. However, it must be noted that this data set misses a lot of data L.1. The missing data accounts for 34 % of the whole set: 617 days of the total amount of 1826 days are missing. This also complicates an accurate outcome of the daily rainfall for different return periods, but the advantage is that it is a novel data set so it does represent the most recent rainfall.

A contributing factor limiting the calculation of the rainfall intensity is the assumed duration. This duration enabled to convert daily rainfall (mm/d) to an intensity in mm/h. Literature study was conducted to come up with a general rain event duration. However, this was difficult to find or the found durations of events were based on a little amount of data. Therefore, the considered durations in this report were set on 1 hour and 3 hours, resulting in high intensity for a short duration and low intensity for a long duration. By just looking at two durations, it might be possible that some events which would result in more flooding are excluded from the research although they could have been found to be relevant for making recommendations.

Another contributing factor which influences the outcome of the rainfall intensity is the assumed threshold for Peak Over Threshold. There are several ways of determining the threshold, and two different methods have been looked into. The highest result of intensities is used to simulate flood maps, as the intensities can be expected to have increased for the data set with period of 1957-1988 due to changing in climate and findings in the TAHMO data set, but of course the chosen threshold remains not completely certain.

When producing the flood maps, not all return periods were considered because this would have result in an extensive amount of flood maps. A return period of 2 years and 5 years have been chosen because the SLAMDAM is easily deployable and mostly used as an emergency measure. Since the SLAMDAM has a lifetime of at least 40 years it can also be implemented in rain events of higher return periods. Nevertheless, these higher return periods are not considered in this report and this should be taken into consideration when interpreting the results, because higher return periods are accompanied by a higher amount of rain so possibly even heavier floods than presented in this report.

The last limitation with regard to calculation of the rainfall intensities and therefore the outcome of 3Di, is the used percentage change of rainfall as a result of climate change. This percentage is derived from climate change predictions for the whole ENN basin so not for the sub-basin itself. Also, this percentage was obtained for the mean annual precipitation instead of the annual maximum daily rainfall for which the percentage is used in this report. Furthermore, the climate change prediction is for a different period than the period of the data set where it has been used for in the calculation. Since no more specific scientific based predictions are available, this percentage was considered to be suitable for the prediction of the climate change-induced rainfall, but the above mentioned limitations should be kept in mind when interpreting the results.

And as discussed in section 7.7.2, the FIS Tool also requires several data sets as input. The created water depth data maps from 3Di are uploaded. Next to this, the damages curves, land use map, and global population maps are being implemented. Because some of these are not entirely in line with the real-life current situations, this is also considered a limitation of the use of the FIS Tool.

So in both tools there is always a gap between digital maps and model results and the reality. This gap is tried to be narrowed by validating the results by conducting interviews with local communities and authorities (see section 9.3.2 and 10.3.1). However, due to different answers and also a discussion within the interviewees some results can not be validated to be 100 % certain. Results were also tried to be validated by visiting some of the sites which seem to be favorable areas to deploy the SLAMDAM and to measure cross-sections. But because of the limited amount of time in Isiolo and deadlines for the SLAMDAM demonstrations, not all sites were visited. Hence it is still possible that some outcomes of possible sites are in reality not as good as the modelled situation predicts. This can for example be the case when land use has changed but when this has not been projected in the land use maps yet, and these outdated land use maps are used as input in the FIS Tool.

Besides these limitations of the input of the tools, both tools make use of several assumptions themselves as well, which were already discussed in section 7.7. There are also other functions found to be not working properly yet. The enumeration of the functions which are currently not working properly are provided in Appendix O, as well as feedback to further improve the software.

Another general limitation is the fact that not all possible scenarios can be modelled. This would require much time and effort for 3Di to compute the flood maps associated with all possible events. A risk associated with not producing maps for unlimited rain events is that there is a chance of not producing the most important or relevant flood maps, and that therefore a key mitigation area can be overlooked. But by looking at rain events on the basis of data sets it has been tried to have enough representing rain events.

With regard to the outcome of the FIS Tool, it must be noted that damages to agricultural area do not take the loss of crops into account. Only the land is used to calculate the damages caused by specific flood depths (Huizinga et al., 2017). With the interviews of the WRUA it has been found that per acre tomatoes or onions around 150,000 to 200,000 KES would be lost if the fields would be destroyed because of inundation. Cheaper crops, such as beans and maize, account for around 50,000 to 70,000 KES loss per acre. This highlights that the FIS Tool underestimates the damages because it only calculates the loss of the agricultural land itself. When one would include the loss of crops, the invisible damages would be a lot higher. It is however very uncertain what kind of crops each farmer produces. There are no clear policies or agreements on which crops can be produced in the area. There is also not a clear overview available showing the produced crops. Therefore it is not possible to show a more exact prediction of the amount of damages on agricultural lands in the results. Next to this there are also tree farmers or livestock farmers which lose there trees and cattle during floods. These lost animal lives are also not visible in the FIS Tool. These losses can also account for up to 50,000 KES per livestock.

The SLAMDAM has also been compared to other flood risk mitigation measures. These measures are evaluated based on criteria which are supported by literature. Even so, many scores remain subjective and are disputable as a result of this. Furthermore, when implementing the infiltration area and retarding basin in the FIS Tool to compare it with the SLAMDAM, it is hard to determine the benefit per invested money due to the fact that it is unclear how much the investment and maintenance costs are of those mitigation measures. Because the FIS Tool does not include these costs of the measure in its calculation, it is hard to compare the outcome of the benefits for different measures and to determine the best measure solely based on the results of the tool. Another contributing factor which complicates good comparison based on the results of the tool is the fact that the FIS Tool does not include additional non-monetary benefits like social, political or cultural benefits. A more general contributing limitation is that only two other mitigation measures besides the SLAMDAM have been used in the FIS Tool to compare the outcome, so much mitigation measures are not included in the comparison.

Another import note for the comparison to other flood risk mitigation measures is the fact that not all possible measures have been considered in the evaluation matrix as well. Only the SLAMDAM and the other measures mentioned in section 6.5 have been evaluated. This can cause that not all available or equally good mitigation measurements have been taken into consideration when comparing measures with the SLAMDAM. Therefore, it could still be possible that another flood risk mitigation ranks higher than the SLAMDAM which now ranks the best.

12.2 Recommendations

Despite the limitations discussed above, the report enables to provide recommendations for the use of the tools and the SLAMDAM.

As a result of mapping of the current flood management in Kenya and as experienced during interactions with stakeholders, it seems to be that flood management has a lower priority than drought management. The existence of the NDMA is one aspect which highlights this. But since climate studies predict an increased flood risk as the result of climate change, it is recommended to assign extra resources into flood management. Since the NDMA is going to be merged with the NDOC and NDMU into the 'National Disaster Management Authority', this would be a good institution to be assigned with the mandate to manage floods. Of course a close collaboration with the WRA is desirable. Also, the matter of the division of responsibilities became clear in the interviews. Many parties mention the strong wish for more clarity in the division of responsibilities as there is now a lot of overlap or, on the contrary, no one takes up a task.

Nevertheless, this does not mean that water resources are not given priority at all. But because of droughts, the focus is more on allocating water resources, water supply and water storage. This is not surprising considering that the majority of the country is ASAL where the scarcity of water for domestic use, irrigation, and drinking poses a higher risk than floods. All in all, the increasing risks of floods caused by among other things climate change should provide enough reason and incentive to increase the resources in flood risk mitigation. This emphasises the recommendation from the previous paragraph that attention should be given in the National Disaster Management Authority and the WRA to flood risk.

It is clear from the formal chart that the Ministry of Water, Irrigation and Sanitation, the national and subregional WRA offices, and the respective WRUA are very important in the decision-making and policy-making process for flood risk mitigation. Since it has been shown how difficult it is to get suitable data and the WRUA knows the project area best, the WRUA is extra important. Also, the WRUA plays a key role in community engagement. It is therefore recommended to private sector companies and others to work closely with these parties. Finally, as with the BWRC, it may take years before the new National Disaster Management Authority is operational. Once this organisation is up and running, collaboration with them is also highly recommended.

In almost all conversations with Kenyan parties problems such as severe weather conditions caused by climate change or dysfunctional drainage systems and broken equipment was mentioned. So during the interaction with stakeholders the relevance of this project was shown. However, while having interviews, site investigations and demonstrations stakeholders were asked about challenges related to project management with specific emphasis on flood risks. From this, attention points were then identified that are recommended when undertaking a project in Kenya.

- *Corruption:* In vain, this is still present, much to the regret of the stakeholder itself. Therefore, be aware of the fact that corruption occurs in everyday activities and create a framework in advance on how best to deal with this.
- *Financial / funding:* Since there may be shortage of available financial resources or priority for other problems, careful consideration should be given to how activity gets funding.
- *Effectiveness of project:* As best as possible, try to determine the output of an intervention measure in advance and avoid organisations or individuals taking the help out of convenience. Thus the solution should be well aligned with the actual problem.
- *Institutional:* Given the short- or non-existing of institutions and that water does not adhere to county or legal boundaries, there is much ambiguity in responsibilities. Who ultimately bears responsibility in a given area to counter flood risk mitigation needs to be made very clear in advance. Consider, for example, who gets ownership of the SLAMDAM and who will deploy it in case of emergency.
- *Data collection:* Obtaining suitable data has proved incredibly difficult. Therefore, schedule enough time for data collection to create more accurate models. More on FEWS will be discussed later in these recommendations. These systems can also be used for data collection.
- *Community engagement:* Crucial in implementing a new technology is acceptance of the local community. Therefore, involve them at an early stage. It is mentioned before, but WRUA is key player in this.

These attention points must be taken into account when starting a project with, in this case, the SLAMDAM. For the feasibility of the SLAMDAM, the Isiolo River Basin was chosen as the main focus area to enable the most accurate recommendations. This basin is located in an ASAL region and probably recommendations for the Isiolo River Basin can also apply for other ASAL regions, which account for 80 % of the country. This is because all ASAL regions can experience the same type of flooding: flash floods. The dryness of the area results in more overland flow rather than infiltration. If the area is low-lying surrounded by high elevation, mountainous areas upstream the water flows fast and can accumulate into the flat area downstream. The arrival times of flash floods can potentially be quite low due to this high flow velocity. Importantly, it does not need to rain in the downstream area itself to result in flooding there: local rainfall upstream can cause flooding downstream. This is the case for Isiolo Town and its surroundings. This sudden arrival of floods complicates preparation for floods and therefore it is highly recommended to implement a Flood Early Warning System in regions like this since flooding is often the result of heavy rainfall upstream, which is not noticeable in the downstream area itself. Sufficient warning must be provided to give time to prepare for the flood.

The SLAMDAM can be used very effectively in combination with Flood Early Warning Systems. When an alert is broadcast, the SLAMDAM can be deployed at the recommended locations to protect against flooding. An advantage of this combination of the FEWS and the SLAMDAM is that this means that the SLAMDAM only gets deployed when really necessary. Many interviewees stated that small floodings are currently used for irrigation, so permanent flood defence systems are probably not desired. A temporary solution like the SLAMDAM is then considered to be a suitable solution.

The recommended locations for deployment of the SLAMDAM are the result of modelling with 3Di and using the FIS Tool to calculate the benefits of implementing the dam at a certain location for a certain length. The areas which provide the highest benefit according to the FIS Tool can be the recommended locations to deploy the SLAMDAM. For the Isiolo River Basin these recommended locations are already provided in section 10.4. However, when keeping the limitations of the data sets in mind, it is also recommended to perform the calculations and simulations again if new and better data is available.

Specific locations recommended for pilots of the SLAMDAM were also provided by Mercy Mbaya from WRA Isiolo (who can be contacted with for further questions about these locations: kedibaya@yahoo.com) and David Mwiti from WRUA Isiolo. These locations were given after the SLAMDAM demonstration and should be interesting for future research for implementing in SLAMDAM in Kenya. The coordinates of the locations are provided below in GPS-coordinates in decimal degrees in the order longitude and latitude:

- Below juja academy: 0.14261, 37.47504
- Along isiolo River: 0.25633, 37.53160
- Upper Ntirimiti: 0.08218, 37.47519
- Kithima: 0.08939, 37.55154
- Kambi Sheik: 0.26980, 37.55080

In the modelling in 3Di, the distance from the SLAMDAM from the river channel has not been taken into account, but it is always recommended to place the dam as far from the river channel to give the river as much space as possible, resulting in less chance of flooding.

To ensure that the locations as result of the tools are in fact feasible for the deployment of the SLAMDAM, all sites must be visited before the dam is transported there. The site must be checked for soil, slope, stream water availability, and presence of an access road to make sure there is a way to allocate the SLAMDAMS next to the river. For example, if there are too much great rocks present, the ground must be cleared beforehand. Besides this, the logistics, with regard to the storage location of the SLAMDAM and the deployment location, should be well arranged and planned out ahead of time. Some recommended sites as outcome of the FIS Tool were not visited for this research due to the limited amount of time, but it is highly recommended to still visit the remaining sites.

With regard to the FEWS, the estimated arrival time can be utilized as lead time of the system. Based on the modelling in 3Di, it is recommended to let it warn for an intensity of 57 mm/h upstream since intensities above this threshold result in much flooding. One can also see that storms that have an intensity of 27 mm/h for a longer duration of 3 hours can result in floods in Isiolo Town.
Based on this and with the information from Table 10.9 it is recommended that if there is a rain intensity of 57 mm/h for a duration for 1 hour, or if there is a accumulated precipitation of 54 mm or more in 2 hours (so 27 mm/h for 2 hour duration or higher), that a warning should be given. When looking at Table 10.9 one can see that for high intensity storms such as 60mm/h, 90mm/h or 81 mm/h the fastest arrival time for a flood event is 5.167 hours. If a storm of 57 mm/h or higher is measured upstream, this would mean a warning and at least 4.167 hours to implement an emergency measure such as the SLAMDAM.

For low intensity rain such as 27, 23, and 30 mm/h it shows that the fastest arrival time for a flood is 7.472 hours. After a 2 hour accumulation of precipitation exceeding 54 mm there would be 5.472 hours left after the warning for emergency measures. The difficulty lies in the fact to search for which threshold is it necessary to switch from a 2 hour accumulation to a 1 hour intensity. This threshold lies between 27 mm/h and 57 mm/h. Because not a lot of rain intensities between these values have been researched upon due to the fact that the rain data with the calculation method from section 7.6.2 did not give these rain intensities, this is something that required more in depth research.

So overall, when this system broadcasts an alert, there are at least 4.167 hours to deploy the dam, as this has been for now the fastest arrival time found after deducing the amount of time before a warning has been given. Depending on the pump capacity, this should be enough time to deploy the dam at the desired place before the flood arrives and the flow velocity becomes too high to pump and it becomes dangerous to be pumping water out of the river. Besides relying on these FEWS, the community also knows when there is a chance of flooding to occur. For the Isiolo River Basin, most floods occur in November or December, so the dam can be placed in October for example and can remain until the risk of flooding decreases.

3Di and the FIS Tool can also be used for other flood risk mitigation measures, as was shown in chapter 11 for an infiltration area and a retarding basin. The evaluated infiltration area has the same location as proposed in the Isiolo Sponge City report by MetaMeta (2022), see chapter 11 for reference. From the calculations using the FIS Tool it is clear that the retarding basin located at the airport can provide significant results in damage reduction, where the initial investment will be earned back in prevented damages after 3 rain events of 60 mm/h for 2 hours. For the infiltration basin it is unclear whether a return of investment is feasible with the current analysis purely based on prevention of flood damages. It is important to look at the scoring matrix in chapter 11 to see which other aspects all the mitigation measures excel in. With this, one can identify key scenarios to implement certain mitigation measures, and not only focusing on the monetary return of a mitigation measure. The monetary aspect of a mitigation is in a lot of cases one of the biggest hurdles to overcome when considering the implementation of an intervention. However, making comparisons one-on-one is not really possible solely based on the outcome of the FIS Tool because the costs of the measure are not taken into account. More research should be done into the specific costs per mitigation measure to be able to define the best mitigation measure with regard to highest return per monetary value spent.

Overall, when considering the recommended use the FIS Tool, it is considered to be most valuable in predicting (also in other areas) beforehand where to deploy the SLAMDAM, how long it must be and how high. This makes it possible for a community to store the SLAMDAM at the most relevant place and it enables fast and effective deployment of the dam. The FIS Tool is less recommended for making comparisons between different mitigation measures, unless the tool will be extended with implementation of the costs for example.

To secure good progress of deployment of the SLAMDAM, there are other aspects which must be in order as well. Good collaboration between upstream and downstream is of great importance for a good execution of the deployment. Besides, the community must be educated to point out the importance of the SLAMDAM and the FEWS, so people will not vandalize these objects. The combination of digital tools and the community must empower each other, raising overall awareness and collaboration in reducing flood mitigation risks. Also, as already became clear from the points of attention, the organisational aspect must be in order. As a result of the stakeholder analysis and their challenges, it is suggested to make the WRUA responsible for the deployment and maintenance whenever the FEWS broadcasts a signal that flooding may occur. Since the WRUA has limited financial resources, it is suggested that the corresponding WRA gets the ownership of the SLAMDAM. Once the National Disaster Management Authority is operational, it is recommended to take over this task from the WRA. To enable fast deployment of the SLAMDAM, the community must be trained on how to deploy the dam beforehand. The KEWI could support in this as they have the mandate for offering training.

The SLAMDAM demonstrations also resulted in recommendations for setting up the dam. A major issue at both demonstrations was the pump and the connecting pipes and hoses. Both times, the usage of the pipes had to be improvised and both times new pumps had to be brought to the site because the initial one did not function properly or function at all. Consequently, it is recommended to deliver the SLAMDAM with a pump and all its pipes and coupling pieces. However, to save costs, using a pump of one of the community members itself must also remain possible. When this is desired, it is recommended to test the pump regularly to see whether it still works properly. In Table 10.9 one can see the arrival time of the flood for the different scenarios to determine a recommended minimum pump capacity. When considering rain events upstream of Isiolo Town, which fall near Timau, warning is required. The shortest arrival time is 5.2 hours for 60 mm/h for which means a preparation time for emergency measures for 4.2 hours. For this scenario 850 meters of a dam is recommended to protect the residential area (see Table 10.2, number 4 in Figure 10.7). To be in time with setting up the dam before the flood arrives, one would need 6 pumps of the advised pumps of 1200 L/min, because one pump can fill 30 units in this amount of time as the biggest SLAMDAM right now can store around 10,000 liter of water, one dam can be filled in around 8 minutes with this pump. However, it would also be recommended to use higher capacity pumps. When one would use pumps of at least 3380 L/min or higher only 2 pumps would be required. However, these pumps are bigger and heavier so may not be desirable. When looking at the longest SLAMDAM solution, which is 1200 meter, it would mean that with a pump of 3380 L/min still 3 pumps are required. Recommended is that for each situation or location specific an advice is given which kind of pumps are needed to be brought with the SLAMDAM, since this is mainly depended on the location-dependent arrival time of the flood and the length of the SLAMDAM.

Storing the water in the dam after the flooding has occurred is highly recommended for ASAL regions, because periods of flooding are often followed up by long periods of droughts. It is most recommended to use the water for irrigation since it became clear after the demonstrations that this was the preference of the community. It proved to be quite a valuable aspect of the dam due to the lack of sufficient irrigation water. The advised type of irrigation for which the water can be used is drip irrigation. Drip irrigation is very efficient and the pressure from the water out of the dam would be too low for sprinkler irrigation. It is important that there is an authority responsible for distributing the irrigation water to prevent conflicts. The distribution of the water can be implemented in the irrigation schemes drafted by the authority.

With regard to future research, it is recommended to also look into the water harvesting of the SLAMDAM in particular, because the interest of all the involved parties was high for this aspect of the dam. For example, Omar Abdullahi Abdi of NDMA Isiolo has mentioned that the SLAMDAM can be a cheaper solution than the conventional storage tank. Future research into the applicability of the water harvesting aspect and the use of the SLAMDAM as a storage tank or retarding basin is therefore of interest, also when considering the fact that the retarding basin scores high in the evaluation when using the FIS Tool. Omar Abdullahi Adbi has recommended to consider a SLAMDAM pilot project near the area where the people are doing some farming activities in the Ewaso irrigation scheme to further complement what NDMA is doing. It is called the Waso project. It is furthermore recommended to look into the quality of the water stored in the SLAMDAM because it is currently unclear what the impact of the EPDM is on the quality of the water stored in the SLAMDAM. This can be tested experimentally.

It is also recommended to do future research in the friction forces exerting on the SLAMDAM. In this report there is no distinguish being made in friction coefficients between the different types of soil interacting with the EPDM material of the SLAMDAM. Interesting would be to see how the strength of the SLAMDAM is calculated with these different friction coefficient of the ground and the EPDM material. To make an accurate estimation, the friction coefficient between the EPDM and different soils should be tested experimentally. The same applies for the maximum water force and velocity the SLAMDAM can resist.

Chapter 13

Conclusion

This research has aimed to find the answer to the following question:

How does the SLAMDAM perform in flood risk reduction in comparison to other flood mitigation techniques using the FIS Tool in the Isiolo River Basin?

To provide an answer to this question, an overview of the current flood situation in Kenya has been provided first. Kenya is most prone to flooding in the rainy seasons from March until May and October until December. These floods are both pluvial and fluvial, so the result of heavy rainfall and river flow. Furthermore, urban areas can experience urban flooding as a result of reduced water infiltration in the subsurface due to the paved area. These impermeable paved areas reduce the infiltration and lead to inadequate drainage. Lastly, flash floods are very common in areas surrounded by steep slopes. A steep slope environment results in rapid water flow and this flow converges in the flat areas downstream of the slopes. ASAL regions, which cover over 80% of Kenya, are more prone to flash floods since overland flow is more likely to occur than infiltration in these dry areas. All these floods are accompanied by severe economic loss and several other losses which contribute to the already high poverty rate in Kenya.

The occurrence of flooding is severely affected by climate change. Climate change studies have already shown that Kenya will be affected extensively: the annual rainfall in Kenya will increase over 20 % by 2100 as a result of climate change. The proportion of heavy events is expected to increase as well, so this increases the risk of flooding. Other scientific models show consistently that the flood magnitude for each type of flooding could increase. Another study suggests that the probability of extreme flood events could get more than tripled by 2100, based on the fact that return periods of these events have already lowered significantly. All in all, the effects of climate change will increase the risk of flooding in Kenya.

With regard to the spatial distribution of the effect of climate change within Kenya, all six basins have been assessed separately. This showed that the ENN basin is relatively most prone to the effects of climate change: the percentage change for mean annual precipitation, surface water, and groundwater potential is the highest in this basin. Therefore, climate change is most likely to influence this basin the most with regard to flooding. In addition, the poverty rate in this basin is already the highest. Since flooding is likely to occur more often in this basin and this results in economic loss which would increase the already high poverty rate even more, this basin especially should be protected against flooding, although the current flood risk management is inadequate.

Within this basin, the Isiolo River Basin is used for an in-depth study to map the current flood risk management and to advise flood risk mitigation measures. This sub-basin includes Isiolo Town, which is a flat ASAL area located downstream from a mountainous area. This town accounts for the vast majority of the population in the Isiolo River Basin and experiences much flooding, mainly flash floods. Isiolo has been identified as one of the flood-prone areas by the National Water Master Plan 2030 which should be protected by river structural measures as well as other non-structural mitigation measures. Within the whole basin there is a high topographic gradient resulting in fast flowing water to downstream and a low flood arrival time. Also, there is mainly clayey and dry soil in the basin, which lead to more runoff instead of infiltration. This runoff is all directed downstream. Other hazards were also identified during the site visit for Isiolo Town specifically. The flow capacity of the Merire River which runs through town is lacking. The flow capacity of the drainage canal is also not sufficient for peak flows and blocked culverts worsen the conditions even more. Another contributing factor to the flood risk is the recently constructed airport. The raised airport grounds redirect water into Isiolo Town that would otherwise flow outside town boundaries.

All these hazards increase the risk of flooding in this region. A possible mitigation measure to reduce this flood risk is the SLAMDAM. The SLAMDAM is a movable flood defence system which consists of compartments with a length of 5 meters each and a height of 1 meter. This dam can be deployed along the river bed to protect areas from flooding, and it can be filled with water from the river. The set up of the dam can be done in a short amount of time, making it suitable for emergencies. The SLAMDAM can be emptied after the flooding has occurred and can be stored for future usage. The water stored within the dam is suitable for irrigation or other water use, which tackles the problem of drought.

To assess the feasibility of the SLAMDAM for the Isiolo River Basin, several tools are used. 3Di has generated flood maps for different rainfall events. The external input for 3Di are rainfall events for different scenarios. One considered scenario is based on information gained from an interview with WRA Isiolo. There used to be a Flood Early Warning System in use which warned at 60 mm/h, so 60 mm/h is used as input for 3Di. Also, rainfall was calculated for different return periods by using extreme value analysis based on maximum daily rainfall for the period 1957-1989 for the Timau Marania Station and the more recent (2017-2022) daily rainfall data from the TAHMO for Isiolo Town. The Timau Marania Station is located in the upstream region of the basin. By modelling the rainfall there locally, 3Di can model the situation where it rains upstream and not in Isiolo Town itself. This proved valuable to model since interviews have concluded that most occurring flood events are a result of intense rainfall upstream of Isiolo Town, and not necessarily in the town itself.

The effect of climate change was also taken into consideration by taking an increase of rainfall of 10.9 % into account. The most critical used intensities and its durations were determined to be:

- 60 mm/h event upstream of Isiolo Town, with a duration of 2 hours.
- 90 mm/h event upstream of Isiolo Town, with a duration of 1 hour, as projected by climate change statistics.
- 67 mm/h event in the whole region, with a duration of 1 hour.
- 27 mm/h event for at least 2 hours (going up to 3 hours), at which then a FEWS should give a warning
- 57 mm/h event for at least 1 hour, at which a FEWS should give a warning

The flood maps generated with 3Di can then be used as input for the FIS Tool. This tool calculates the benefits for placing the dam at a certain location for a certain length. From the model simulations, six possible locations for the deployment of the SLAMDAM are selected. Some of the modelled recommended sites were also visited to see whether the modelled situation coincides with the real life situation. The site has to meet some conditions: there must be presence of water to fill the dam, the terrain must be fairly flat and the soil must not be sandy. Based on FIS Tool and the site investigation the preferred locations to implement the SLAMDAM are location 1 and 2 in Figure 13.1. These locations meet the boundary conditions for the deployment of the SLAMDAM (chart 10.10). This is due to the location being easily accessible by road, next to having enough water flowing to preemptively pump up the SLAMDAM. Furthermore, the gradients of the bank are flat enough for the SLAMDAM to not roll over while pumping and there are no obstacles to remove to make space for the SLAMDAM. The further away from the water source you place the dam, the more storage capacity and room for the river it provides. Location 3 and 4 are less suitable, mainly due to the necessity to remove the obstacles (trees, rocks, etc.), which are currently not giving enough space for the SLAMDAM to be efficiently deployed. Next to this, the topographic gradient is too steep for deploying the SLAMDAM without running the risk of it rolling over during pumping. Lastly, during the site visit the amount of water available was limited and it is not clear whether there is enough water to fill up a SLAMDAM ahead of time. Locations 5 and 6 (Figures 10.8 and 10.9) could still be suitable locations but were not visited physically due to the limited amount of time available for the project.

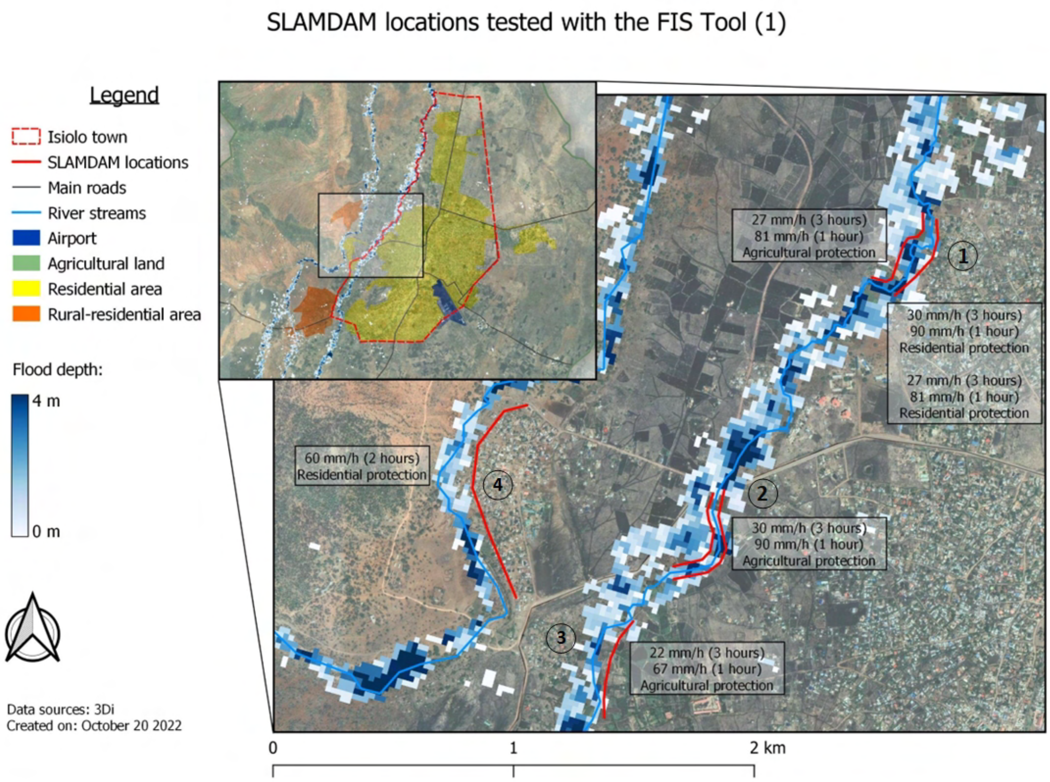


Figure 13.1: Possible locations for implementing the SLAMDAM based on FIS Tool simulations and verified with a site investigation

The FIS Tool in combination with a site visit enables one to provide solid recommendations about where to deploy the SLAMDAM and how long and high the dam must be. In this way, the most relevant location to store the SLAMDAM can be determined.

Since in this basin mostly flash floods occur, the SLAMDAM is highly recommended in combination with a Flood Early Warning System. As floods are often sudden and the result of extreme rain events upstream, which are not noticeable downstream, the community downstream must be warned. The threshold for the warning is now recommended to be set at an intensity of 57 mm/h or if there is an accumulated precipitation of 54 mm in 2 hours or less. When there are enough pumps with enough pump capacity, this would provide enough time to deploy the SLAMDAM. The recommended minimum pump capacity is 1200 L/min but often more or stronger pumps are required to use at the same time for fast deployment in case the FEWS warns.

To avoid to become fixated solely on the SLAMDAM, other flood mitigation measures were also evaluated and compared with the SLAMDAM. The risk assessment for Isiolo Town has shown there are many blocked culverts. Development of the drainage system in the town can therefore be a good solution to reduce the risk of flooding. Another measure could be forestation, which increases infiltration of water into the subsurface and adds multiple benefits other than flood risk mitigation. It is a common practice being implemented in the Isiolo River Basin ever since the occurrence of large scale deforestation in previous years. Excavation or widening of the river bed is an example of an effective flood risk mitigation measure, yet it is not advised to implement when looking at the costs and the local disruption and heavy machinery required for it to be effective. Based on the ranking of each measure for different criteria, the SLAMDAM, the development of drainage systems, and forestation score the best in total amount of points.
To enable a better comparison, the FIS Tool has also been used to compare the SLAMDAM with two of the considered mitigation measures. The retarding basin on the Isiolo Airport grounds and infiltration areas were modelled in 3Di. These have been evaluated with the help of the FIS Tool. However, the FIS Tool does not enable one to make comparisons solely based on the outcome of the tool, mostly because the costs of the measures are not taken into consideration. But after performing some calculations, the SLAMDAM and the retarding basin were found to provide high benefits in reduction of flood damages using a 60 mm/h storm with a duration of 2 hours as input. A return of investment will be met after the occurrence of two to three 60 mm/hour rain events with a duration of 2 hours. It is unclear whether the infiltration basin will provide a return of investment solely on reduction of flood damages. However, the infiltration area provides various other benefits (environmental, social, financial, cultural) which can be enough incentive to implement the mitigation

measure.

This comparison of the SLAMDAM with other mitigation measures by using the FIS Tool provides an answer to the research question. The SLAMDAM performs best in the Isiolo River Basin when looking at both the evaluation matrix and the outcome of the FIS Tool under the notation that only two other measures than the SLAMDAM were considered in the FIS Tool.

So overall, the outcomes of the comparisons by both the matrix and the FIS Tool determine that the SLAMDAM performs very good compared to the other considered flood risk mitigation measures. However, there are some recommendations for proper deployment of the SLAMDAM. Most importantly, the pump must work properly. The pumps must be checked regularly to see whether they still function as desired and the presence of the right hoses and pipes must also be checked. Furthermore, from the interviews and all the other interaction with stakeholders, attention in project management must be paid to the following aspects:

- Corruption
- Financial resources / funding
- Effectiveness of project
- The different institutions and their responsibilities
- Data collection
- Community engagement

It is recommended to let WRUA be responsible for the deployment, storage, and the maintenance of the SLAMDAM. The ownership of the SLAMDAM should be assigned to the corresponding WRA. Once the National Disaster Management Authority is operational, it is recommended to take over this task from the WRA. Lastly, when the water inside of the SLAMDAM will be re-used for irrigation purposes as is highly recommended in ASAL regions, the distribution must be performed equally. This can be implemented in the irrigation schemes which are already in operation.

Overall, the 3Di and the FIS Tool are particularly found to be valuable in enabling one to recommend particular sites to deploy the SLAMDAM in case of need. In this way, it is possible to find a good location to store the SLAMDAM to enable fast deployment in case of need. The overall conclusion is that the most effective measure for the Isiolo River Basin would be the SLAMDAM in combination with a FEWS. In this way, the community can be alerted in time and can set up the dam in time before it gets too dangerous. In this way, digital tools and the community can empower each other.

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Appendix A

Landforms Kenya

A.1 Mountains and major scarps

A natural elevation of the earth's surface rising from the surrounding. The relief intensity is 300 m or more, relative to adjacent elevation.

A.2 Volcanic Footridges

Landforms that consist of broad parallel, rather convex interfluves altered by deeply incised valleys.

A.3 Footslopes and Piedmonts

The term footslope is used to describe the lower portion of a hillslope.

Piedmonts are flat, wide gently sloping surface of low relief flanking an upland area. Often they are cut by stream erosion.

A.4 Piedmonts Plains

A plain located at the foot of mountains or hills.

A.5 Plateaus and High-level Structural Plains

A plateau is an elevated flat ground, generally bound by an abrupt scarp.

High-level structural plains are relatively flat areas underlain by a horizontal strata which is unequally resistance to weathering.

A.6 Uplands and Dissected Peneplains

Surfaces of accumulation and erosion. These landforms are undergoing processes of degradation.

A.7 Floodplains

Strips adjacent to river channels. They are made of alluvium deposited during floods.

A.8 Lowlands

Land that is formed by depressed topography.

Appendix B

Map of the landforms and soils in Kenya

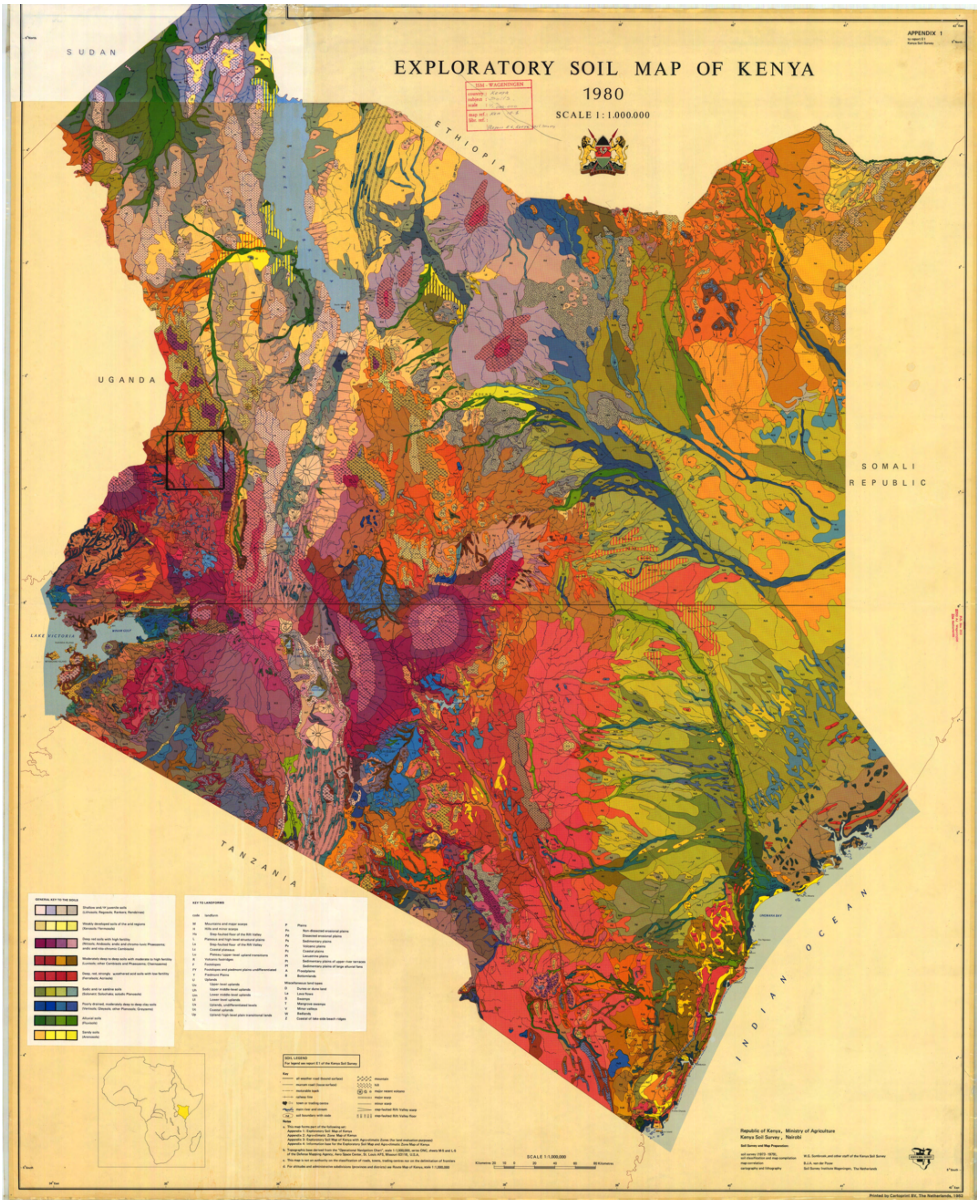

Figure B.1: The landforms and soils in Kenya (Panagos et al., 2011)

Appendix C

Land cover classification in Kenya

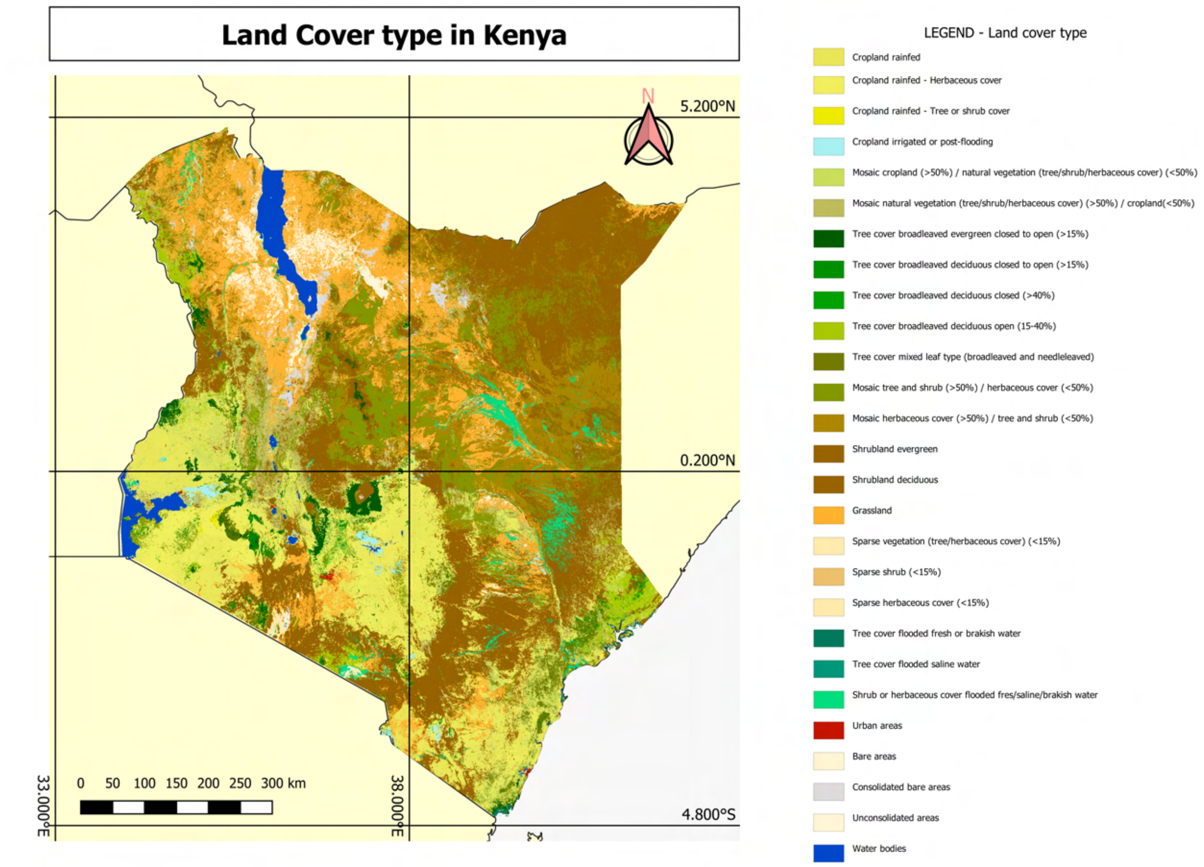

Figure C.1: Land cover type in Kenya, obtained from the ICPAC geoportal (ICPAC, 2015)

Appendix D

Isiolo River Basin delineation

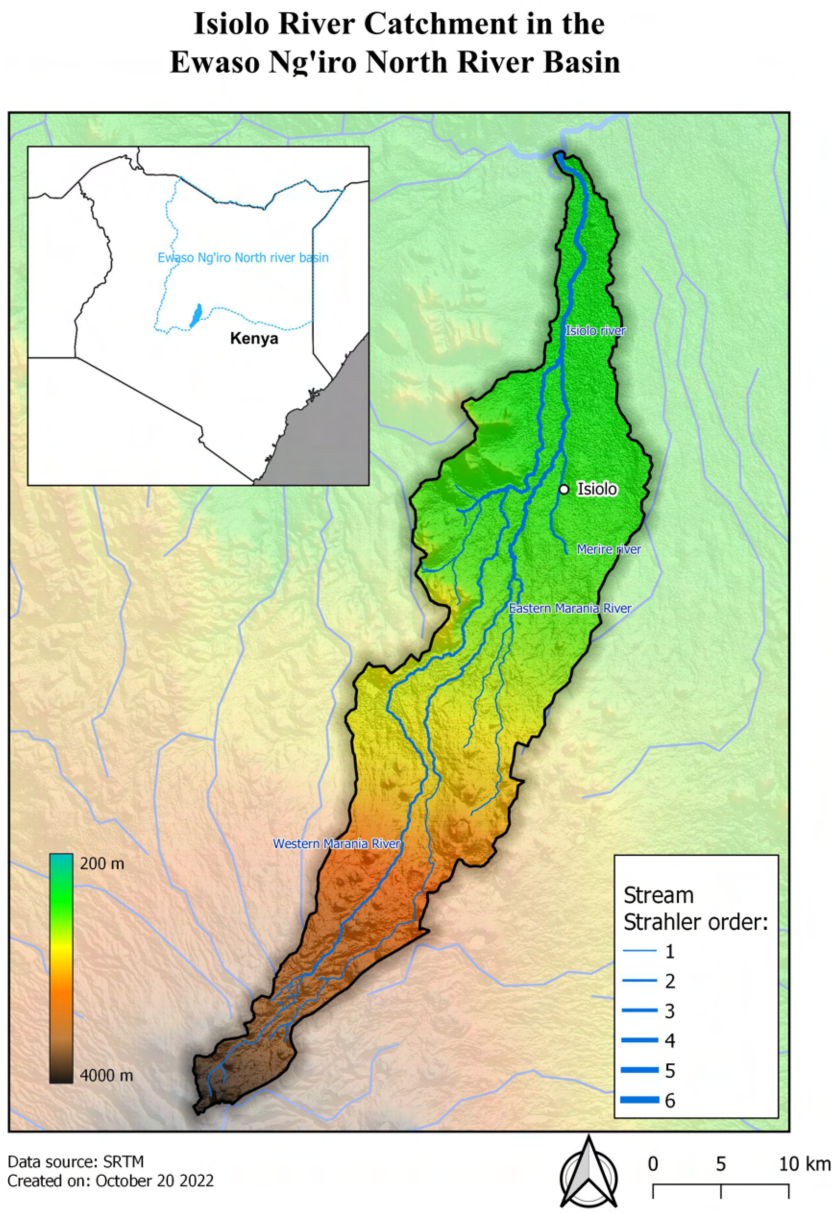

Figure D.1: Isiolo River Basin delineation, height data obained from the SRTM mission (Farr et al., 2007)

Appendix E

Usage and Storage of SLAMDAM

PLEASE NOTE THE FOLLOWING DURING AND ÀFTER USING THE SLAM*DAM*®:

- **Check the subsoil** and remove any sharp items, like rocks, before you install the SLAM*DAM*®.
- Make sure that the bottom of the SLAM*DAM*® contains **as less folds as possible**, so the SLAM*DAM*® can shift into the right shape which leads to maximum stability and water content in the SLAM*DAM*®. If the bottom does contain folds, the SLAM*DAM*® will not be able to shift into its optimal shape on the subsoil. When this occurs, there will be unnecessary water leakage and the SLAM*DAM*® will offer insufficient protection; the functionality of the SLAM*DAM*® might be at risk, as regards to stability as well, filling the SLAM*DAM*® plus water leakage.
- **Sharp objects** might bring damage to the SLAM*DAM*®, which makes the SLAM*DAM*® inoperative. The functionality of the SLAM*DAM*® might be at risk, as regards to stability as well, filling the SLAM*DAM*® plus water leakage.
- It is **important** that the SLAM*DAMS*® follow each others lines exactly, in order to guarantee stability.
- It is of utmost importance **to make a 2 to max 4 cm overlap**. You place the one SLAM*DAM*® 2 cm over the other for good closure and watertightness. The first SLAM*DAM*® you fill, must be placed with an overlap of 2 cm on the following SLAM*DAM*®.
- Do not refill the SLAM*DAM*® when using! As soon as the plugs are loosened and removed, the SLAM*DAM*® deflates under great pressure and the SLAM*DAM*® fails, because the flood water exercises an enormous pressure on the SLAM*DAM*®.
- The SLAM*DAM*® should **not** be moved during use.
- **No** external forces may, unlike the flooding itself, be exerted on the SLAM*DAM*®.
  No vehicles (such as cars or tractors) may bump into or push against the SLAM*DAM*®, to change the position.
- The SLAM*DAM*® is tested according the PAS1188:2-2009 method.
  The SLAM*DAM*® may **only** be used in the following situations:
  - The water level to be defended rises to a maximum of 50 cm in stagnant water.
  - The maximum current of the water parallel to the SLAM*DAM*® is 1 meter per second, of which the maximum water level is 41.6 cm.
  - The wave action has a maximum height of 0.2 meter and the water level to be defended is 50 cm.
- The SLAM*DAM*® is composed of sustainable material and is UV, rain and water resistant. The SLAM*DAM*® can be stored at any location. Despite the UV resistance, storage in direct sunlight is not recommended. A storage building in which the SLAM*DAM*® does not come into contact with sharp items is preferred.
- The SLAM*DAM*® **cannot** be exposed to fire.

Figure E.1: Usage and storage of SLAMDAM (SLAMDAM, 2016)

Appendix F

Guidelines for using SLAMDAM

- The SLAMDAM® is a sustainable product and is composed of EPDM. EPDM is a material with an expected lifetime of more than 40 years. The rubbers of the SLAMDAM® sealing plugs have to be replaced after 10 years. These can be ordered at SLAMDAM® B.V. Welds of SLAMDAM® also have a firm capacity of 5 years.
- Regular checks on the SLAMDAM® are recommended when in use. The frequency of the checks has to be consulted with the emergency services (such as the fire department), since it is dependent of the risk level, the situation and the environment.
- Make sure you check the SLAMDAM® for damage before and after every use. In case of any damage, please contact SLAMDAM® BV.
- The SLAMDAM® height is 67 cm and offers protection against a flood level of 50 cm. In case the water still rises (the so-called 'overtopping'), please put a second SLAMDAM® stretcher bond behind every installed SLAMDAM®, preventing displacement.
- The SLAMDAM® withstands salt water and polluted water.
- If one or both compartments burst(s) during use, it will lose shape, leading to failure of the SLAMDAM®. Therefore, two SLAMDAMS® are placed stretcher bond behind the leaking SLAMDAM®, to guarantee the stability of the flood defence of the SLAMDAMS®.
- The SLAMDAM® is tested according the PAS1188:2-2009 method. The test results were positive up to a maximum of 50 cm water pressure, under surveillance of TÜV Nederland. The test results and the aspects examined have been included in a TÜV Nederland Test report (2013-A-322 : reference).
- Consumer(s) of the SLAMDAM® have to ensure the use of the correct personal protection aids and instruct any bystanders as appropriate. SLAMDAM® cannot be used for any other purposes.

Appendix G

Interview question form used for site investigation

Local community in Isiolo Town

- When were the last floods you remember (in the past 5 years)? Date and time.
- Where did the most severe floods occur?
- How high did the water come?
- What was the duration of the flood?
- What are important sites or buildings to protect against flooding according to you?
- (What damage did the flood cause (you)?)

Farmers

- When were the last floods you remember?
- How high did the water come?
- What are the effects of flooding for your land? (e.g. loss of crop or livestock or sediment deposit)
- How much money do you make per hectare (or related per crop)? (So how much money would be lost in case of flooding)
- Do you also depend on small occasional floodings for irrigation?
- What techniques do you have in place to control flooding in your farm?
- Would a mobile dam which collects water be suitable for you?

Appendix H

Data and sources of the Isiolo River Basin

Figure H.1: List of data used to formulate the methodology of the report and their sources

Data sources on the Isiolo River catchment			
Data	***Acquisition (year)***	***Source***	***Extra info***
DEM	2007	SRTM30-mission	Resolution of ~30 x 30 m. Highest resolution DEM file available to us.
Soil classification	1982	ICPAC	Originally acquired by the Kenyan Soil Survey in 1982 and revised multiple times.
Land cover	2015	ICPAC	Resolution of ~ 310 x 310 m. Most up to date land cover map.
Rain gauge measurements		CETRAD	N.A.
Rain gauge measurements	09/2017-09/2022	TAHMO	van de Giesen, Nick, Rolf Hut, and John Selker. "The trans-African hydro-meteorological observatory (TAHMO)." Wiley Interdisciplinary Reviews: Water 1, no. 4 (2014): 341-348
Rain gauge measurements	1957-1989	KMD, JICA	Rainfall calculations and measurements of various stations
Stream gauge measurements	2019-2022	CETRAD	Stream Gauge measurements of various stations in Isiolo County (5DA08, 5DE01, 5DA04)
Stream gauge measurements	1976-2013	WRA Nanyuki	5D08 ISIOLO stream gauge. Measured once per month during flooding season.
Flood peak runoff	1957-1989	KMD, JICA	Flood peak runoff based on rainfall measurements and rational formula: *Q = 1/3.6*f*r* A (Government of Kenya, 2013)*
Population data	2022	FIS	Information generated using ABM-Tool
Population data	2009	CETRAD	Population of the Isiolo River Catchment as well as the ENN basin
Land use	2022	Open Street Map	Open source collaboratory database
Land use	2017-2022	Impact Observatory, Microsoft, ESRI	Sentinel-2 ~10 x 10 m
Damage curves	2017	European Union	Damages per land use category per country
Agricultural damages	2022	WRUA members	Damages per acre per type of agricultural land
Flood Hazard maps	2016	European Union	Flood maps at global scale from riverine floods
Flood Hazard maps	2022	3Di	Resolution of ~30 x 30 m. Results generated from model schematisation
Catchment delineation	2016	SNV	Catchment boundaries of the Isiolo WRUA
River streams	2016	SNV	River streams in around the Isiolo River Catchment
Town and road infrastructure	2022	CETRAD	Town and road locations in the Catchment area
DEM	2007	CETRAD	Resolution ~50 x 50 m
Base maps	2007	WRI Africa	Delineation of water basins, catchments , main rivers, and flood plains
Administrative boundaries	2009-2022	Natural Earth	Country boundaries
Global rainfall	2018	GPM	Resolution of ~10 x 10 km

Legend	
(red)	Use in 3Di
(yellow)	Use in FIS
(green)	Background and comprehension of site
(blue)	Hydrology
(white)	Other

Appendix I

Manning friction values per land cover type in Isiolo Catchment

Table I.1: Manning friction values used in hydrological model of the Isiolo River Basin (ICPAC, 2015).

Land cover type	Manning friction value (-)
Cropland rainfed	0.03
Cropland rainfed - Herbaceous cover	0.03
Cropland irrigated or post-flooding	0.035
Mosaic cropland (>50%) / natural vegetation (tree/shrub/herbaceous cover) (<50%)	0.035
Mosaic natural vegetation (tree/shrub/herbaceous cover) (>50%) / cropland(<50%)	0.04
Tree cover broadleaved evergreen closed to open (>15%)	0.12
Tree cover broadleaved deciduous closed to open (>15%)	0.1
Tree cover broadleaved deciduous open (15-40%)	0.1
Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	0.1
Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	0.05
Shrubland evergreen	0.06
Grassland	0.04
Bare areas	0.03
Consolidated bare areas	0.025

Appendix J

SLAMDAM demonstrations

Isiolo: SLAMDAM and FIS – tool technology
Presentation & Demonstration

Location: **Kisimani Eco Resort, Maili Saba**
Starting time: **10.00 AM**
Date: **19 October 2022**

TIME	ITEM
9.45 am	Arrival and registration at Kisimani Eco Resort
10.00 am	Welcome Address and kick-off
10.10 am	Opening remarks (objectives for today)
10.20 am	Introduction of all members present
10.30 am	Invitation of project of students TU Delft (in English)
10.45 am	Presentation of FIS tool (in English)
11.00 am	Presentation of the SLAMDAM-technology (in Kiswahili)
11.30 am	Q & A Session
12.00 pm	Deployment of SLAMDAM (demonstration at site, walking distance of resort)
13.00 pm	Group Photograph
13.15 pm	Vote of thanks / Closing remarks
13.30 pm	Refreshments and return to Kisimani Eco Resort Guests leave at own pleasure

Figure J.1: Agenda of the SLAMDAM demonstration near Isiolo. The agenda for the demonstration in Kiambu was similar.

Figure J.2: Presentation of the FIS Tool and SLAMDAM, October 19 2022, Maili Saba.

Figure J.3: SLAMDAM demonstration, October 19 2022, Maili Saba.

Figure J.4: Presentation of the FIS Tool and SLAMDAM, October 21 2022, Kiambu.

Figure J.5: SLAMDAM demonstration, October 21 2022, Kiambu.

Link to newspaper article in 'Nation' about the SLAMDAM demonstration in Maili Saba (near Isiolo Town), Sunday, October 23, 2022:

https://nation.africa/kenya/counties/isiolo/isiolo-farmers-trained-on-floods-management-3994962

Appendix K

Pictures site investigation

Figure K.1: Blocked culvert in Isiolo Town, observed during the site investigation on October 4 2022.

Figure K.2: Blocked culvert in Isiolo Town, observed during the site investigation on October 4 2022.

Figure K.3: Blocked culvert in Isiolo Town, observed during the site investigation on October 4 2022.

Figure K.4: Drainage canal along the A2 in Isiolo Town, observed during the site investigation on October 4 2022. The person is around 180 cm as reference.

Appendix L

Calculations Annual Maxima and Peak over Threshold

Figure L.1: Location Map of Rainfall and Water Level Gauging Stations (Republic of Kenya, 2013)

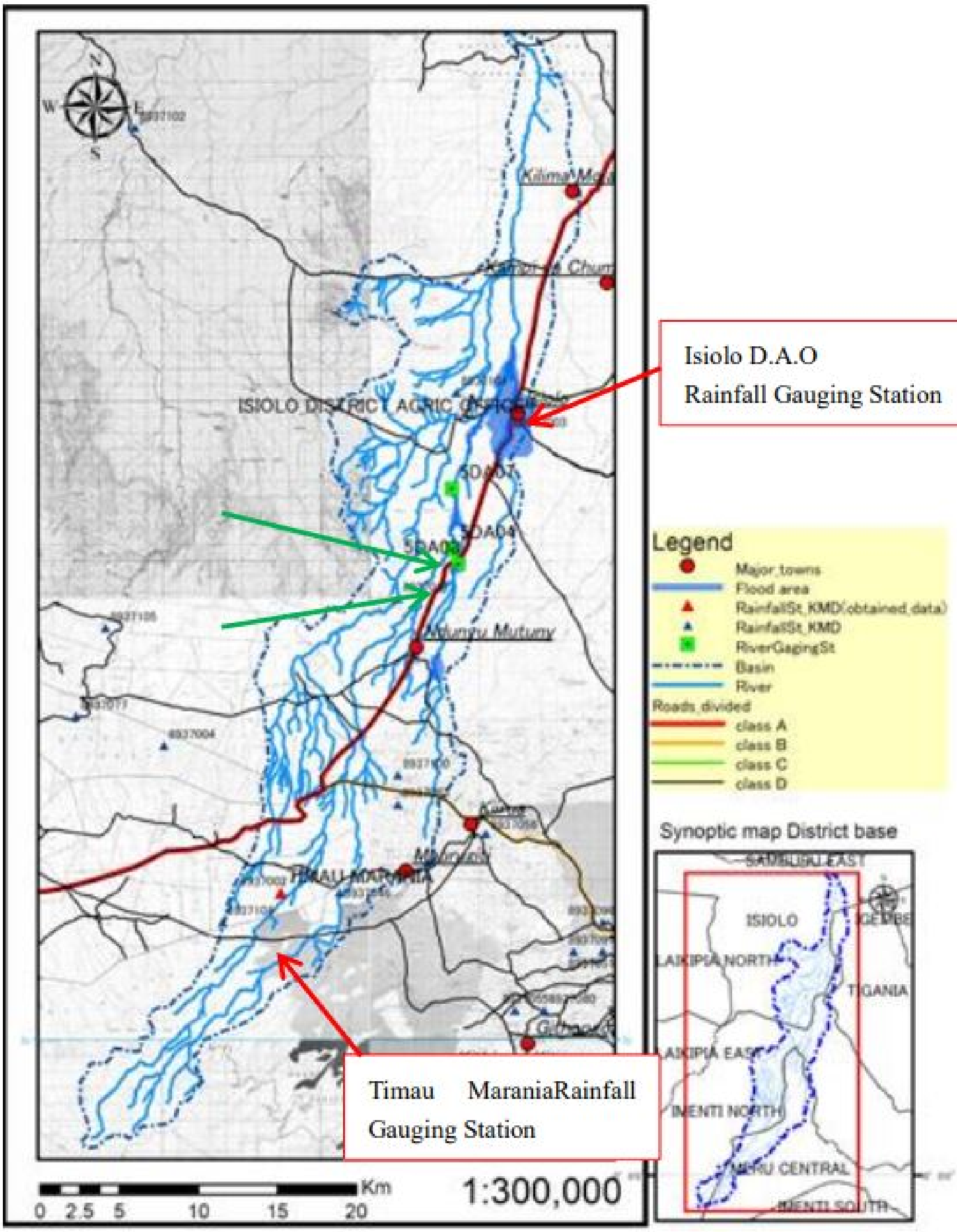

Figure L.2: Observation Record at Timau Marania Station (Republic of Kenya, 2013)

Year	Date	Maximum Daily Rainfall [mm/day]	Annual Rainfall [mm/yr]	Number of missing data	Period of missing data
1957	1957/10/29	85.6	872	32	1/1-2/1
1958	1958/04/26	67.1	667	0	
1959	1959/12/11	114.3	823	90	1/2-4/1
1960	1960/10/25	51.8	751	0	
1961	1961/12/14	104.6	1,737	28	2/2-3/1
1962	1962/10/12	33.8	645	0	
1963	1963/05/29	63.0	1,161	0	
1964	1964/04/18	64.0	975	0	
1965	1965/03/25	26.4	414	0	
1966	1966/03/29	43.2	703	0	
1967	1967/11/26	52.1	985	0	
1968	1968/04/03	94.0	1,278	0	
1969	1969/05/02	84.3	865	0	
1970	1970/10/15	51.1	625	0	
1971	1971/04/27	61.7	631	0	
1972	1972/06/22	54.1	815	0	
1973	1973/04/15	32.9	640	0	
1974	1974/11/07	52.8	849	0	
1975	1975/11/17	42.6	740	0	
1976	1976/12/14	42.3	634	30	9/2-10/1
1977	1977/11/07	68.8	1,008	0	
1978	1978/11/26	49.4	1,052	0	
1979	1979/02/01	75.8	1,097	0	
1980	1980/10/19	62.5	775	30	9/2-10/1
1981	1981/11/07	65.3	1,173	0	
1982	1982/10/29	73.2	1,214	0	
1983	1983/12/28	127.7	1,093	0	
1984	1984/11/15	75.6	837	0	
1985	1985/11/12	65.1	775	0	
1986	1986/10/26	63.4	1,119	0	
1987	1987/06/04	64.7	723	0	
1988	1988/12/21	67.8	1,537	0	

Source : Prepared by JICA Project Team based on the observation data of the period of 1957 to 1989 at KMD owned Timau Marania Rainfall Gauging Station.

Figure L.3: Observation Record at Isiolo DAO Station (Republic of Kenya, 2013)

Year	Date	MaximumDailyRainfall [mm/day]	AnnualRainfall [mm/yr]	Number of missing data	Period of missing data
1957	1957/05/28	65.3	737	0	
1958	1958/11/06	35.6	455	0	
1959	1959/11/24	60.5	550	59	1/2-3/2
1960	1960/11/17	38.4	593	0	
1961	1961/11/25	61.0	1261	28	2/2-3/1
1962	1962/04/22	43.7	689	62	1/2-2/1, 10/2-11/1
1963	1963/11/15	79.7	859	0	
1964	1964/05/02	27.0	209	243	1/2-3/1, 6/2-9/1, 10/2-12/31
1965	1965/09/21	52.0	309	94	1/1-2/1, 5/2-6/1, 7/2-8/1
1966	1966/04/13	64.1	682	30	9/2-10/1
1967	-	0.0	0.0	183	3/2-6/1, 10/2-12/31
1968	1968/11/27	80.8	1243	1	1/1
1969	1969/05/03	70.0	906	0	
1970	1970/05/28	53.1	296	213	6/2-12/31
1971	-	0.0	-	-	No data
1972	-	0.0	-	-	No data
1973	1973/03/28	38.6	475	1	1/1
1974	1974/11/08	36.7	498	0	
1975	1975/04/18	85.2	475	0	
1976	1976/02/26	49.2	624	0	
1977	1977/03/23	42.1	646	0	
1978	1978/10/13	44.8	807	30	6/2-7/1
1979	1979/04/10	62.3	726	0	
1980	1980/11/10	47.7	528	0	
1981	1981/05/03	30.3	467	0	
1982	1982/03/10	97.0	763	0	
1983	1983/04/27	84.1	555	0	
1984	1984/11/08	65.4	535	0	
1985	1985/11/05	48.0	581	0	
1986	1986/10/10	38.8	694	0	
1987	1987/04/23	82.9	638	0	
1988	1988/03/25	55.2	717	0	

Source : Prepared by JICA Project Team based on the observation data for the period of 1957 to 1989 at KMD owned Isiolo DAO Rainfall Gauging Station

Figure L.4: Location TA00172 Isiolo Meteorological Service, TAHMO station (van de Giesen et al., 2016)

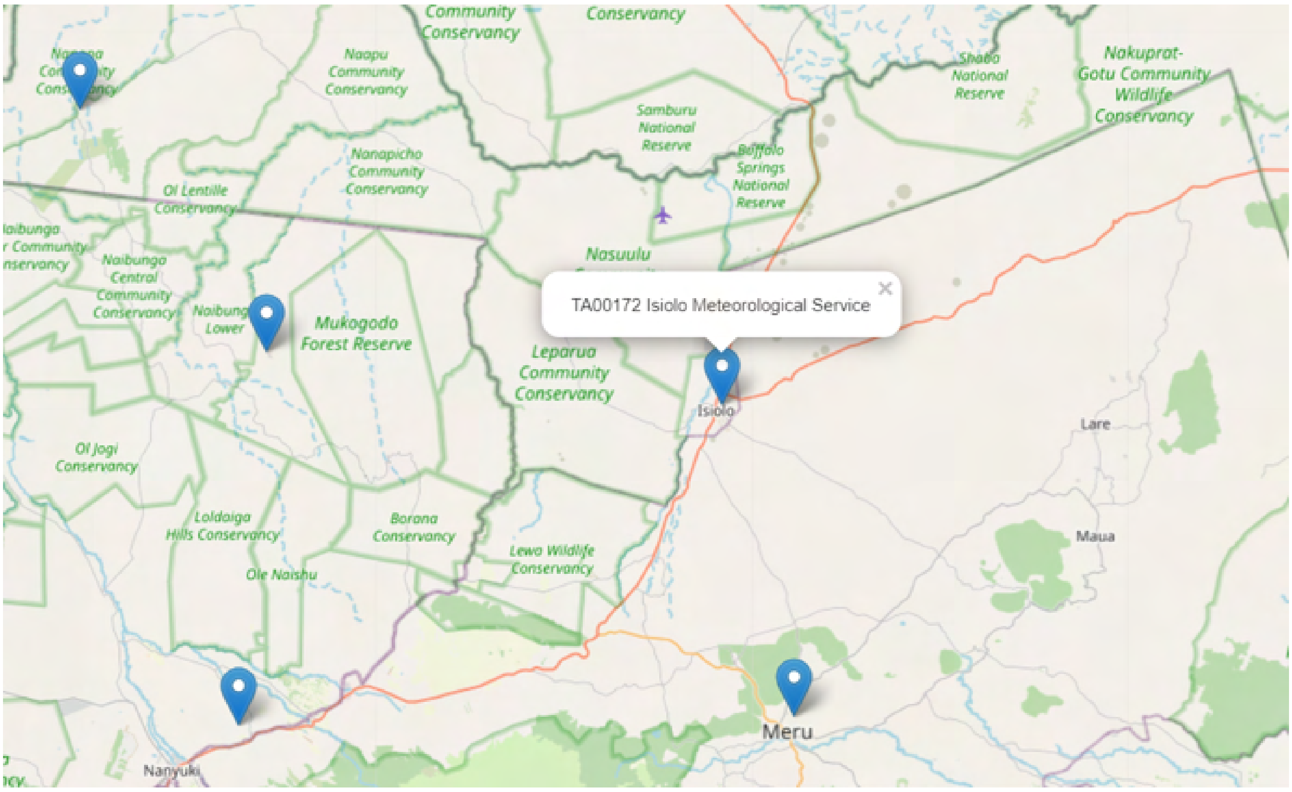

Table L.1: Annual Maximum Daily Rainfall & Missing data in TAHMO dataset

Year	Maximum Daily Rainfall [mm/d]	Date	Number of missing data	Start period of missing data	End
Sep-2017 to Sep-2018	24.939	07/11/2017	297	08/11/2017	31/08/2018
Sep-2018 to Sep-2019	36.783	03/06/2019	42	01/09/2018	12/10/2018
Sep-2019 to Sep-2020	103.7	11/12/2019	0	-	-
Sep-2020 to Sep-2021	59.317	07/12/2020	187	18/01/2021	23/07/2021
Sep-2021 to Sep-2022	53.482	17/01/2022	91	01/10/2021	30/12/2021
		Total:	617		

Appendix M

Flood maps

Flood maps created in 3Di for different intensity storms and duration. Each map shown is in order it showed in Chapter 9.3.2.

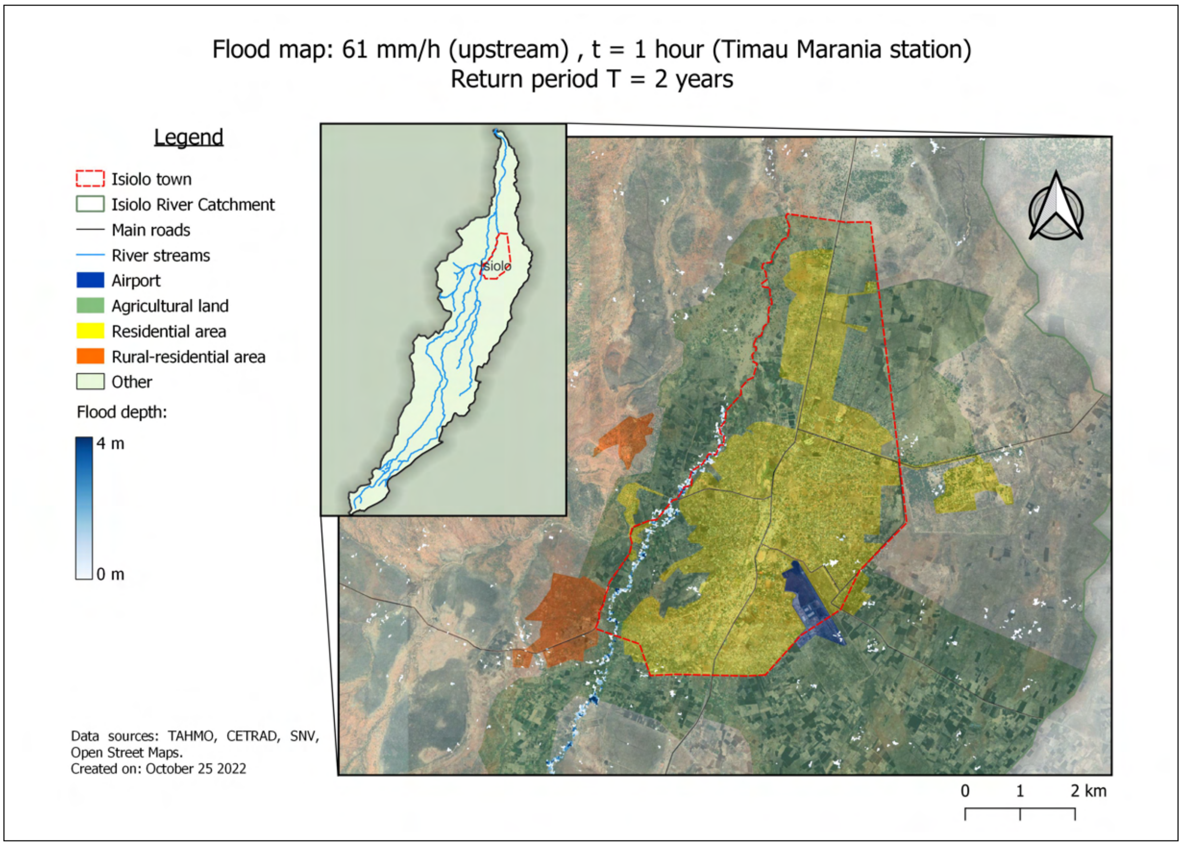

Figure M.1: Flood map of 61 [mm/h] intensity storm (duration: 1 hour) created in 3Di

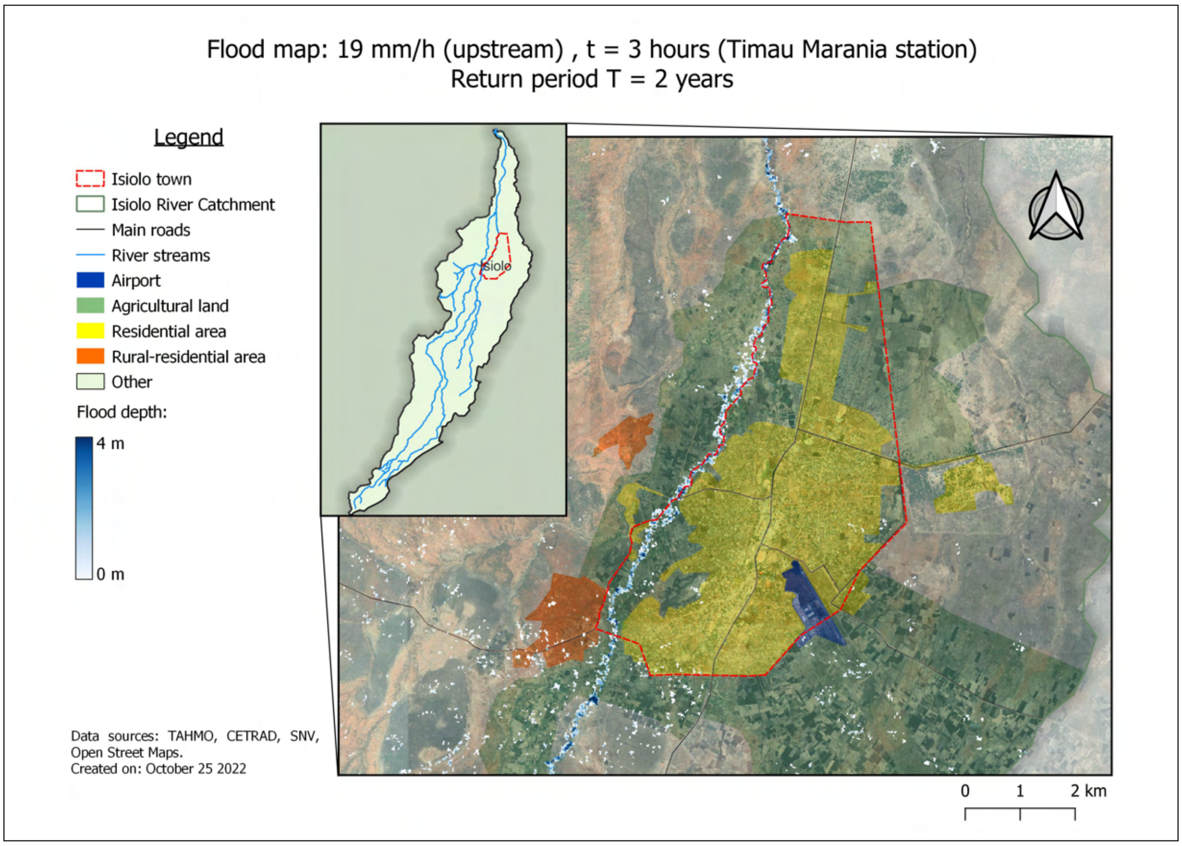

Figure M.2: Flood map of 19 [mm/h] intensity storm (duration: 3 hours) created in 3Di

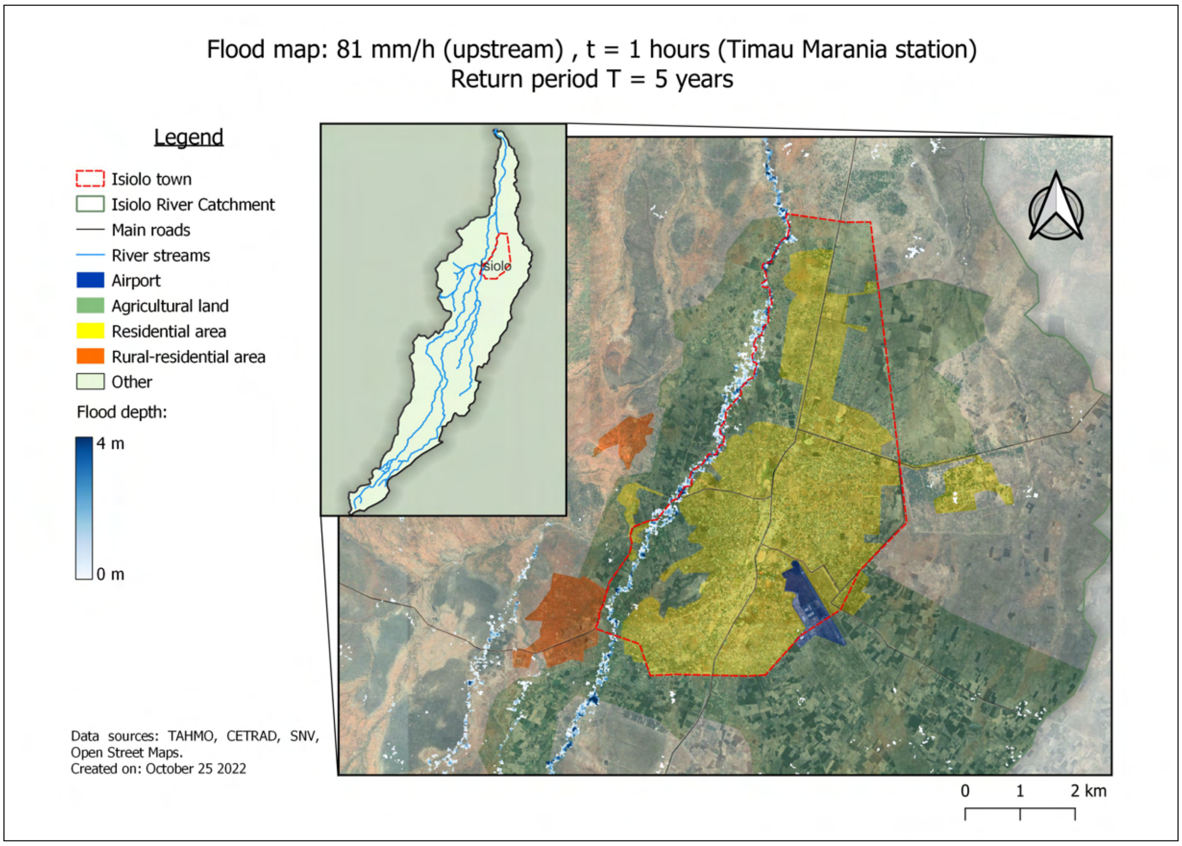

Figure M.3: Flood map of 81 [mm/h] intensity storm (duration: 1 hour) created in 3Di

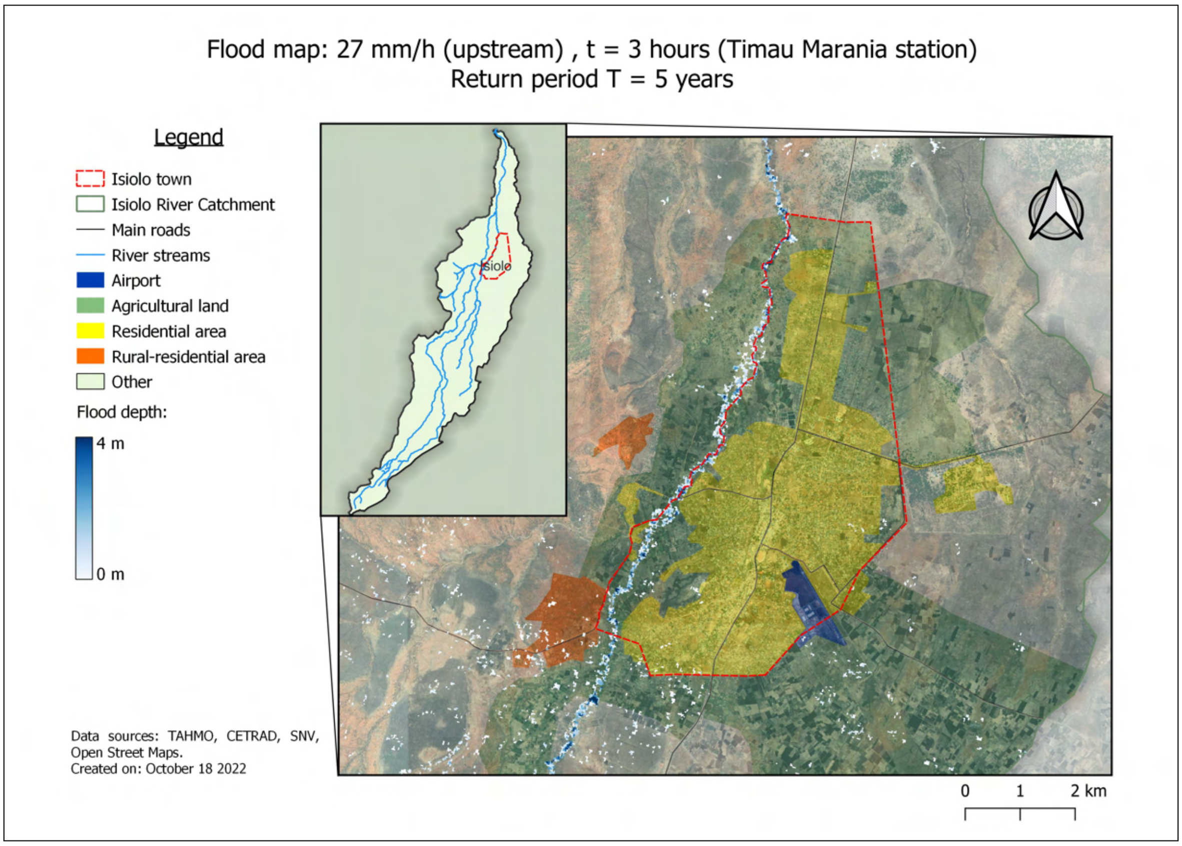

Figure M.4: Flood map of 27 [mm/h] intensity storm (duration: 3 hours) created in 3Di

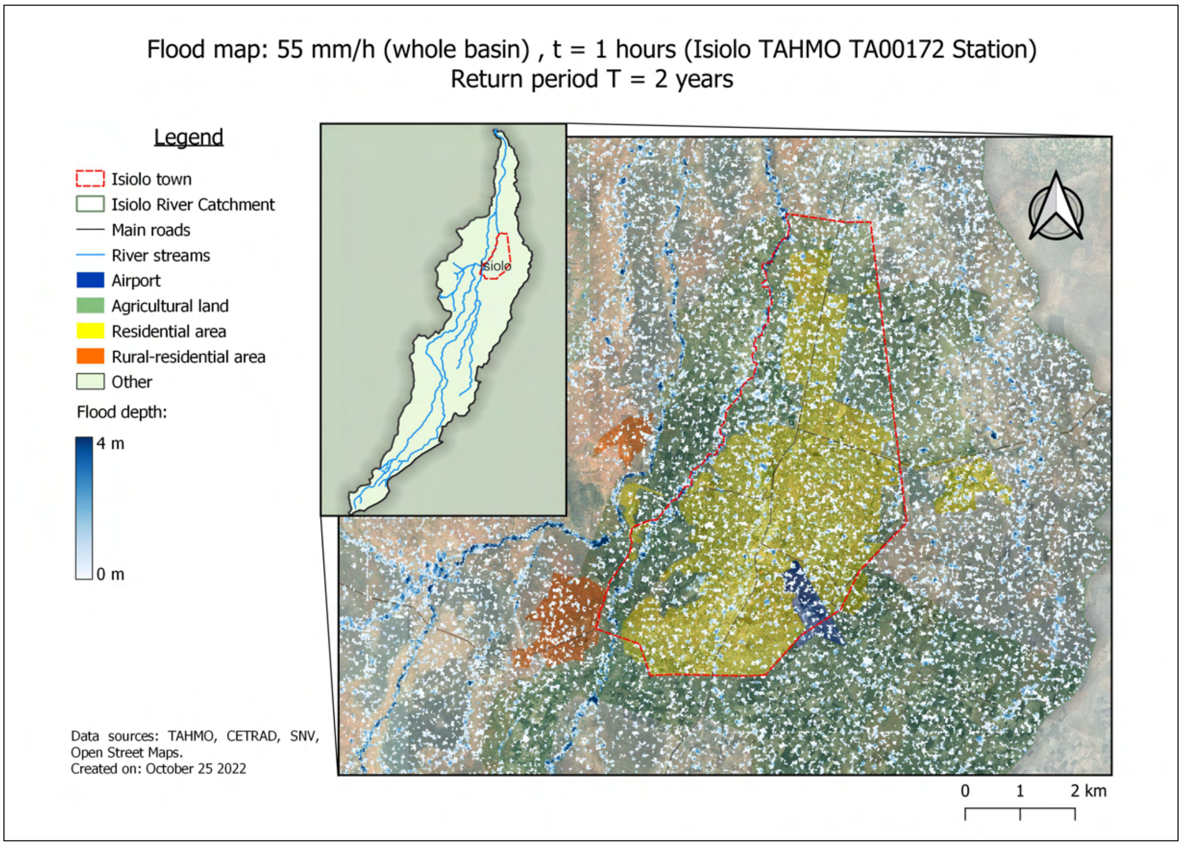

Figure M.5: Flood map of 51 [mm/h] intensity storm (duration: 1 hour) created in 3Di

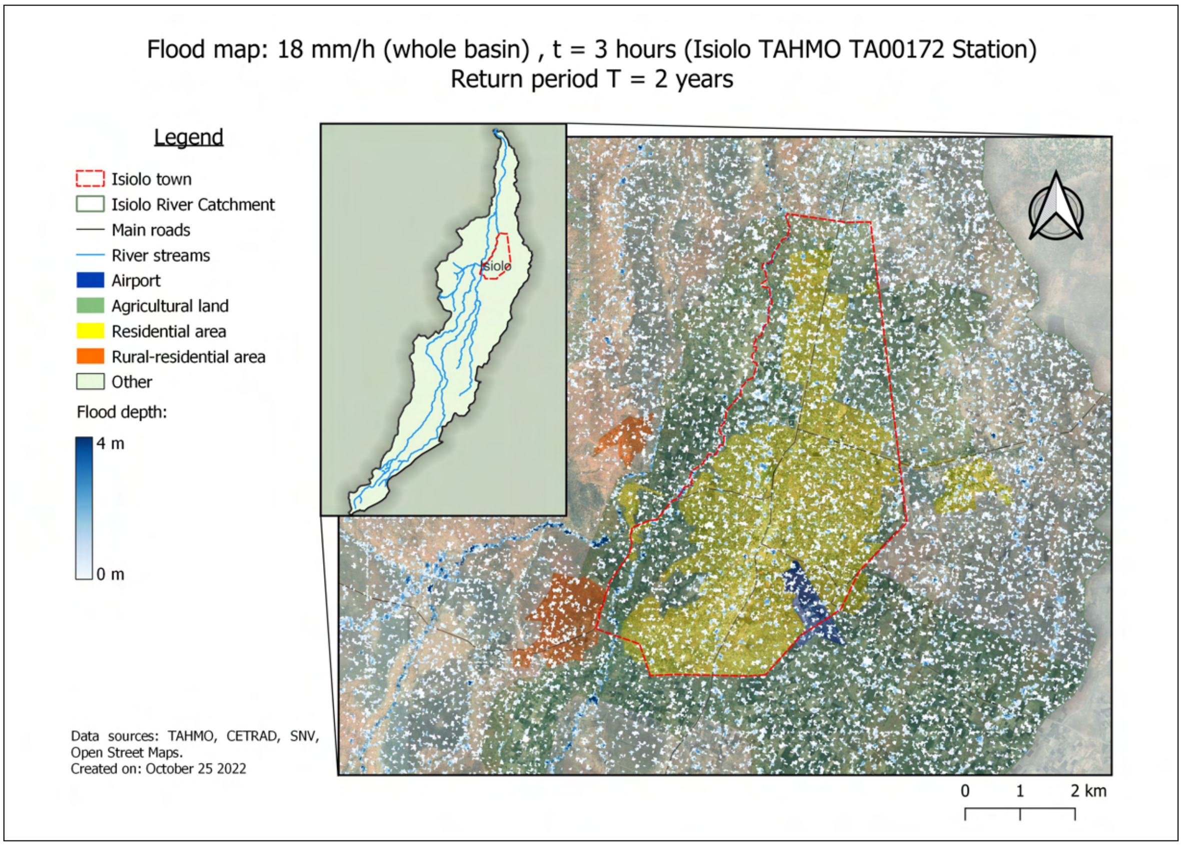

Figure M.6: Flood map of 18 [mm/h] intensity storm (duration: 3hours) created in 3Di

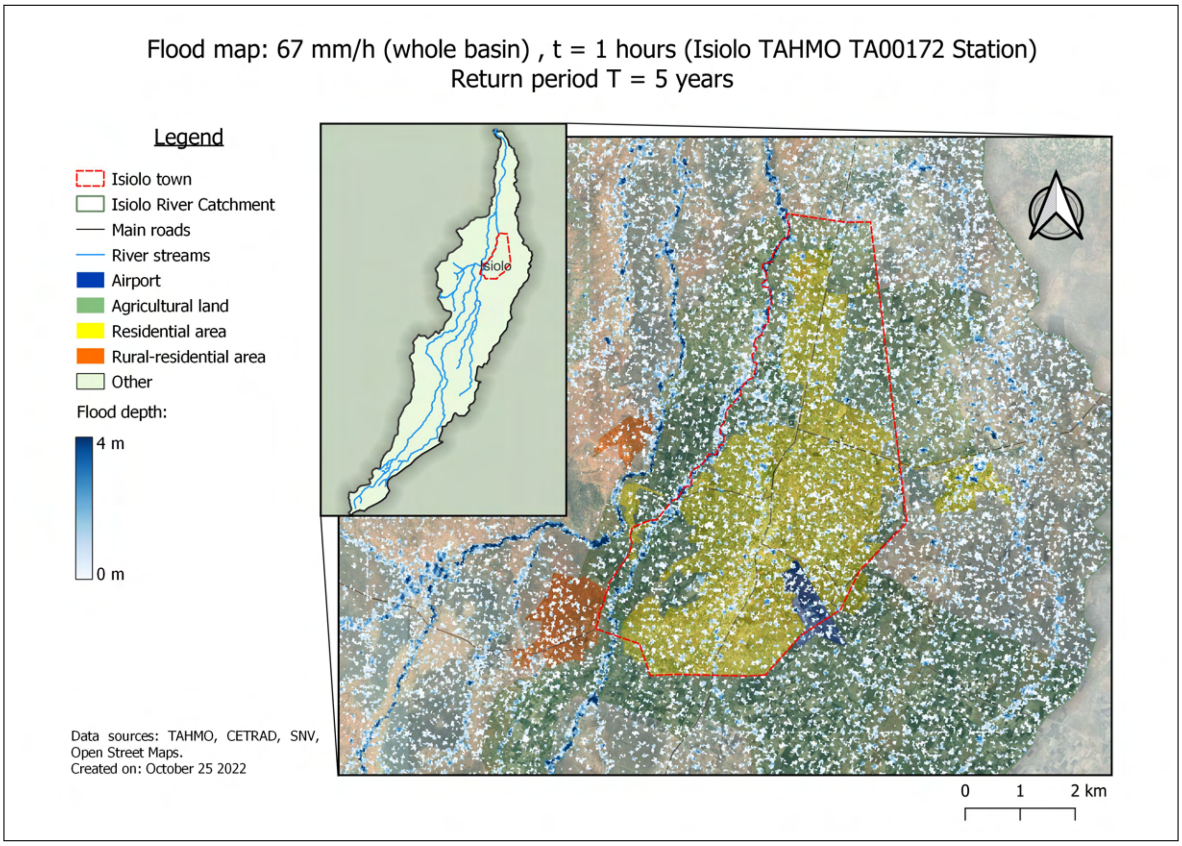

Figure M.7: Flood map of 67 [mm/h] intensity storm (duration: 1 hour) created in 3Di

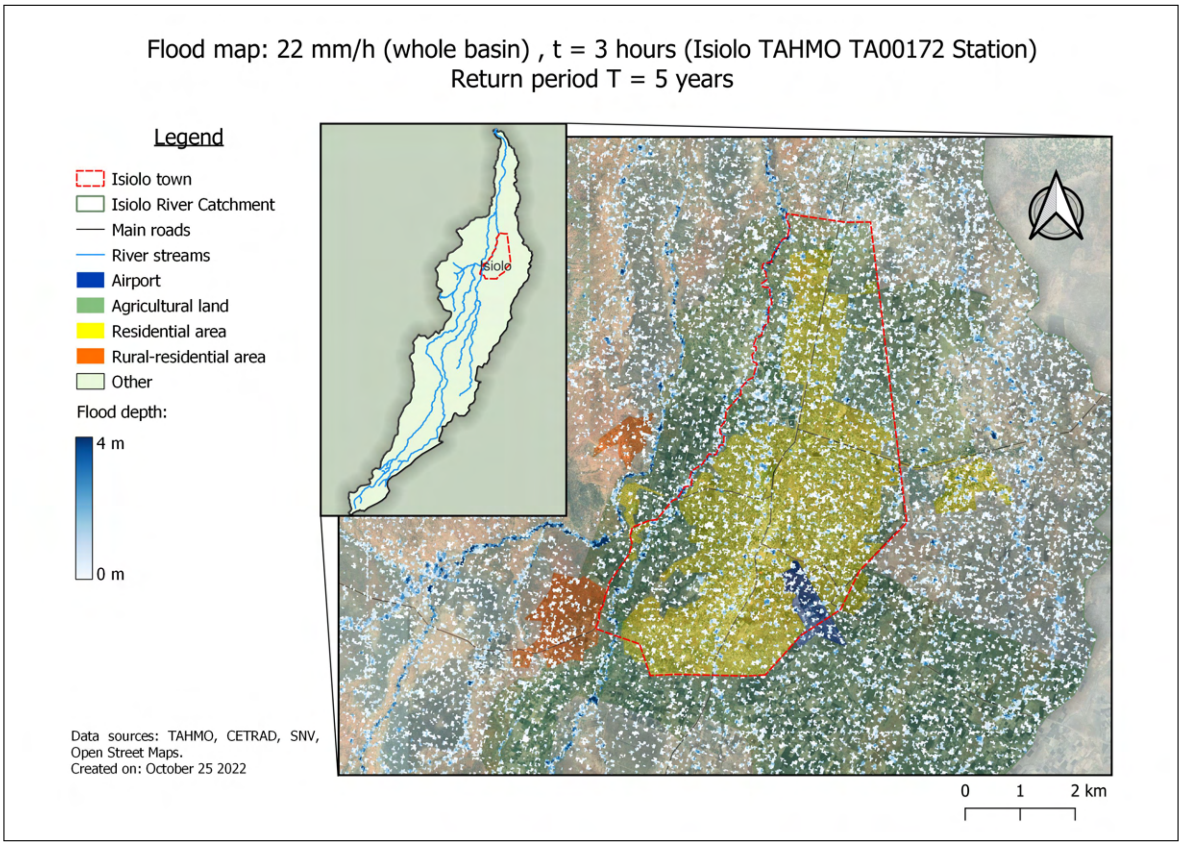

Figure M.8: Flood map of 22 [mm/h] intensity storm (duration: 3 hours) created in 3Di

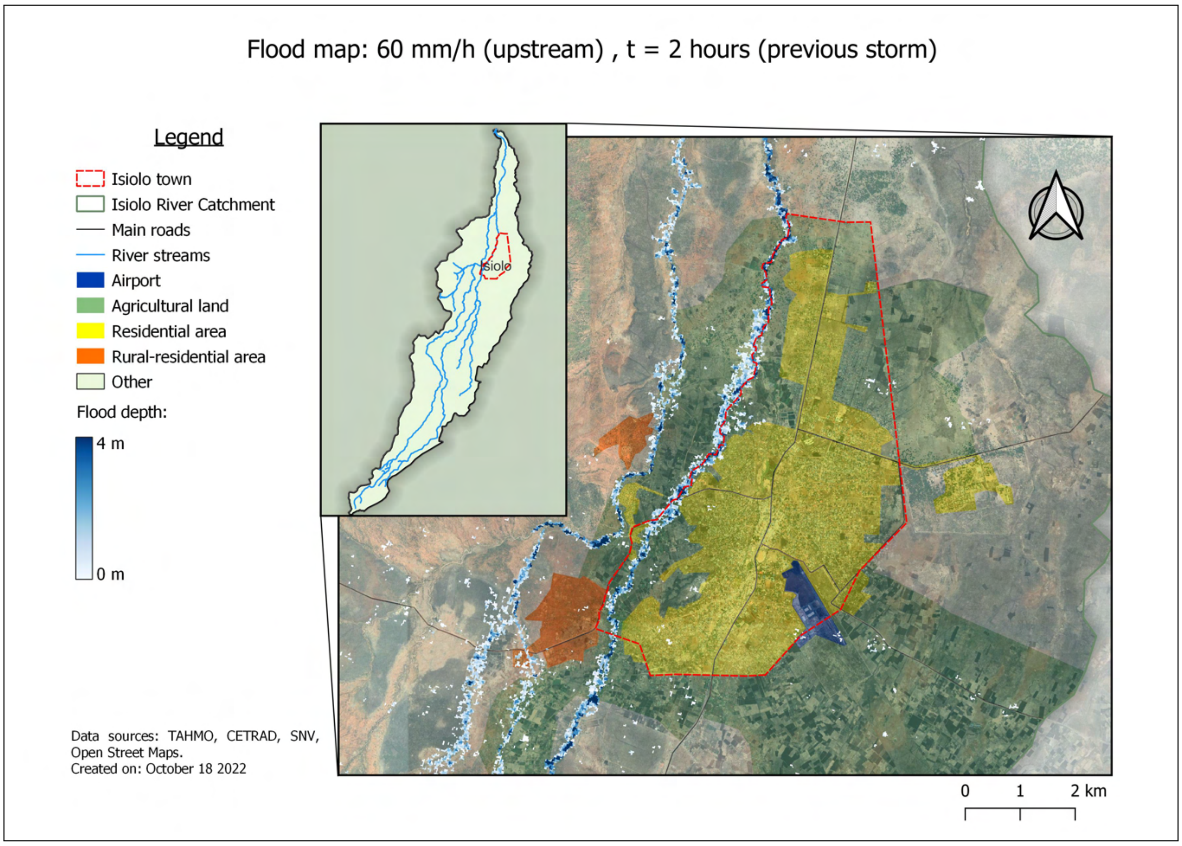

Figure M.9: Flood map of 60 [mm/h] intensity storm (duration: 2 hour) created in 3Di

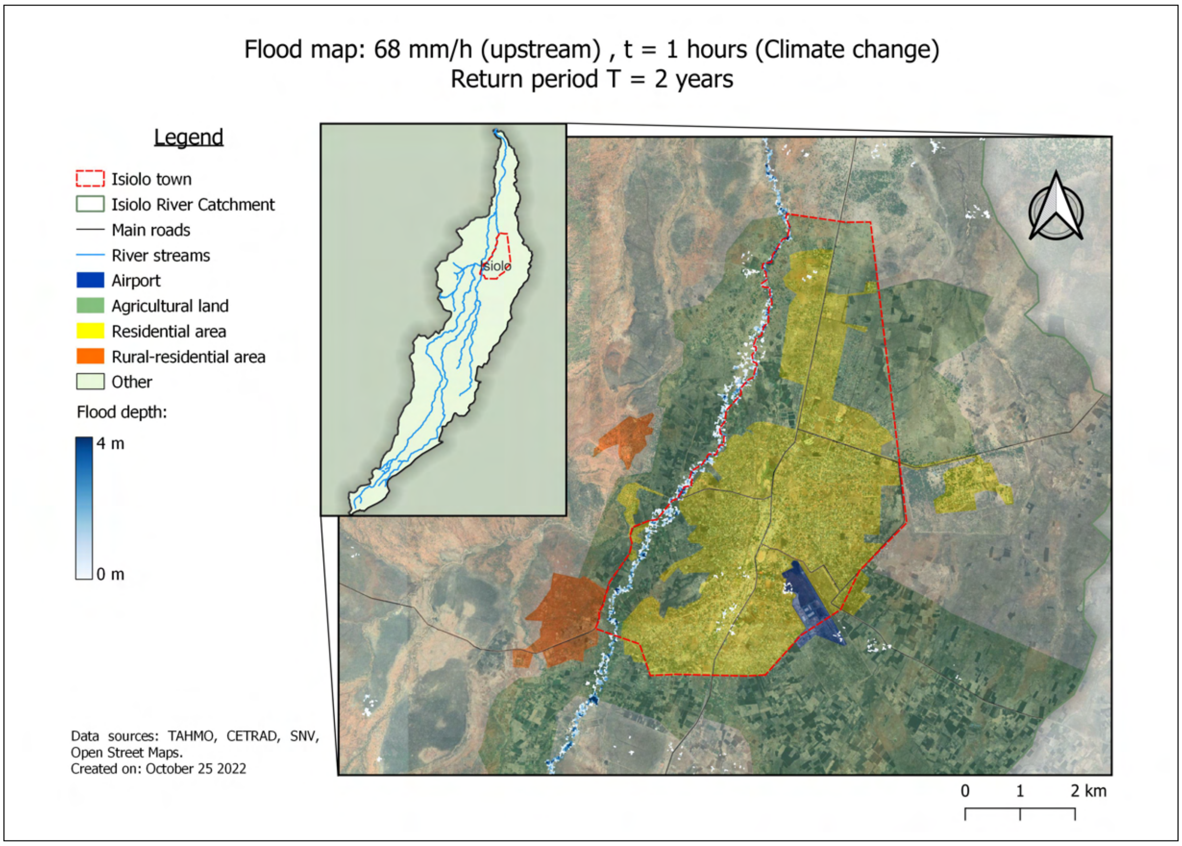

Figure M.10: Flood map of 68 [mm/h] intensity storm (duration: 1 hour) created in 3Di

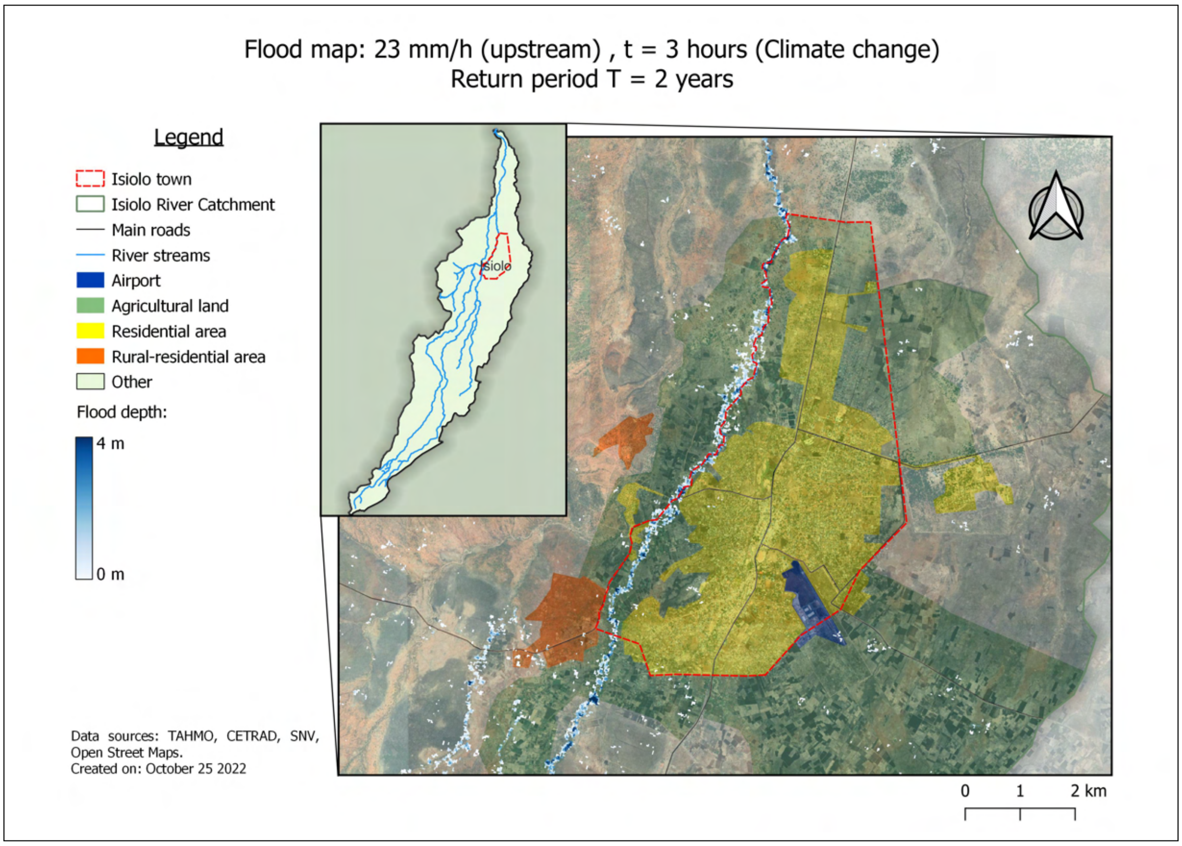

Figure M.11: Flood map of 23 [mm/h] intensity storm (duration: 3 hours) created in 3Di

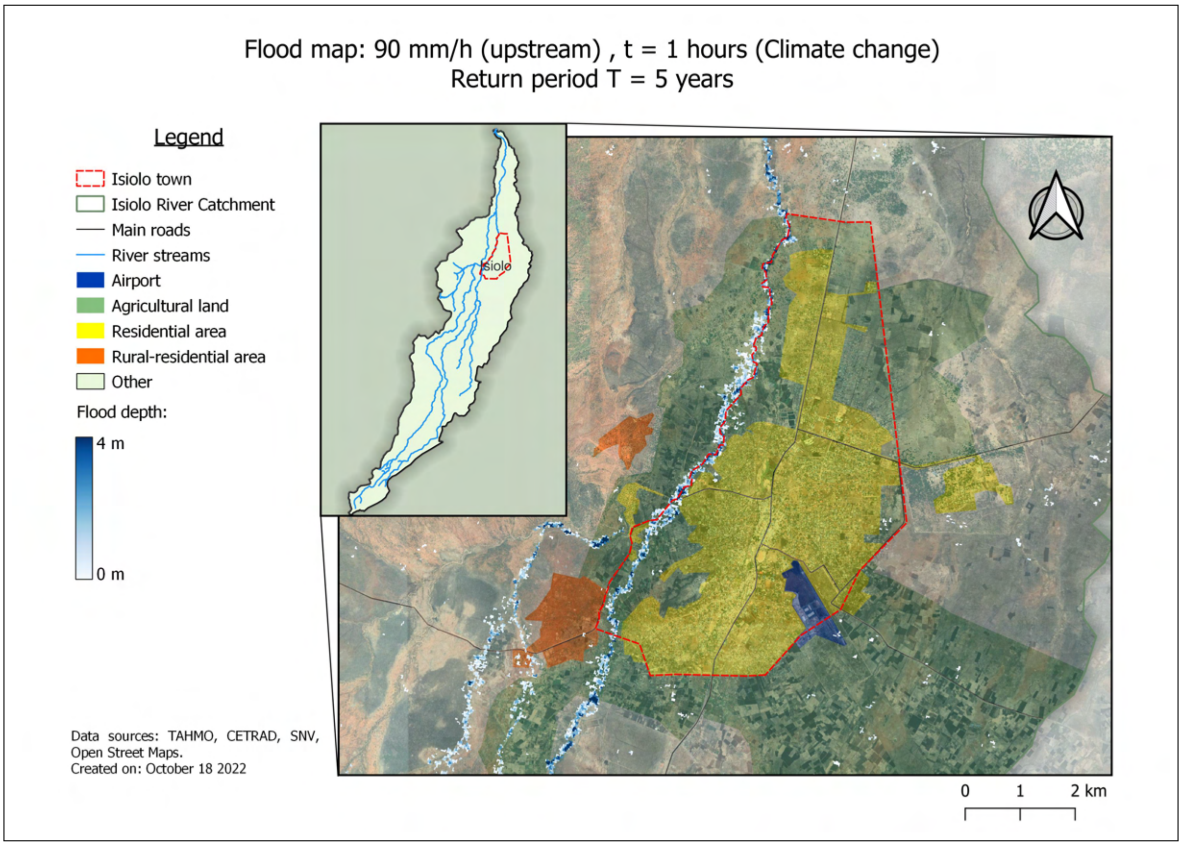

Figure M.12: Flood map of 90 [mm/h] intensity storm (duration: 1 hours) created in 3Di

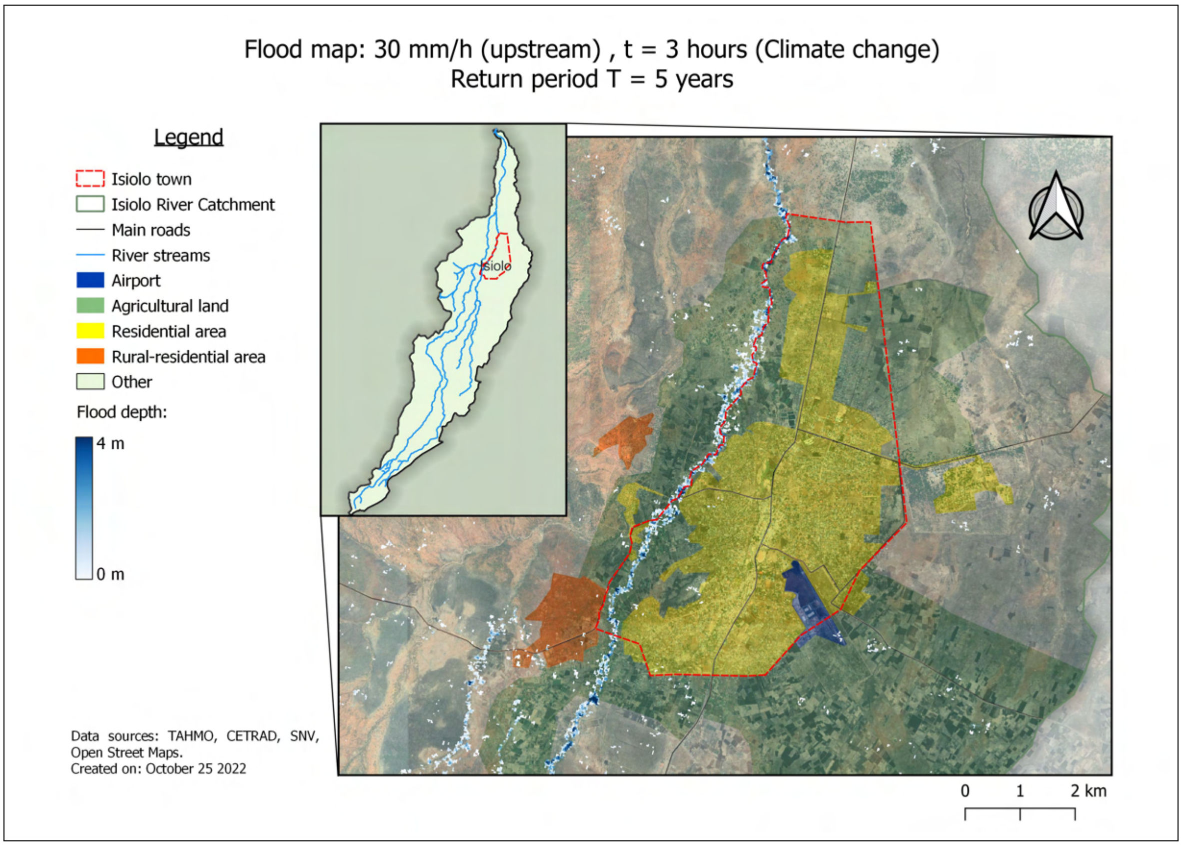

Figure M.13: Flood map of 30 [mm/h] intensity storm (duration: 3 hours) created in 3Di

Appendix N

Flood maps Retarding basin and Infiltration area in Isiolo Town

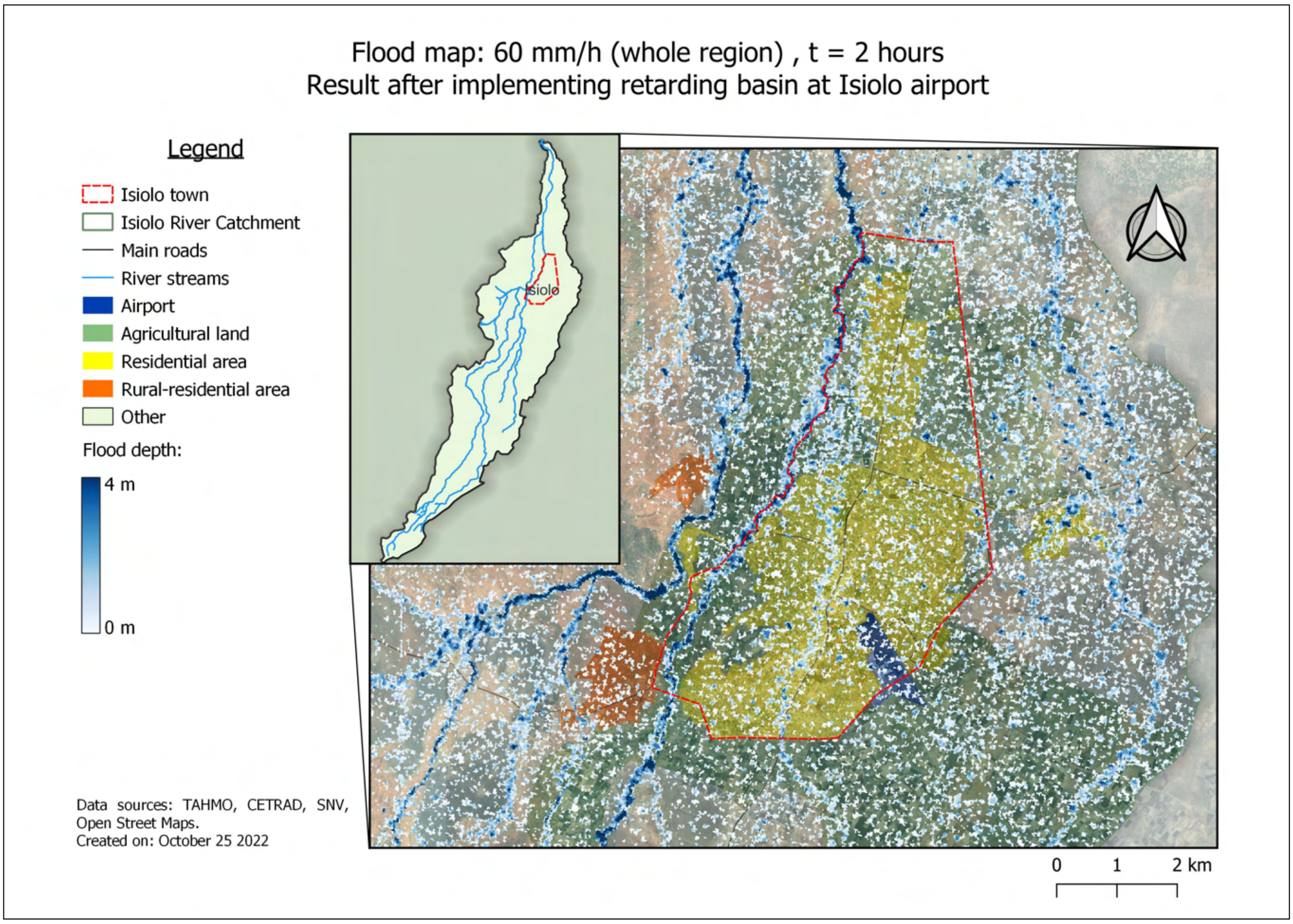

Figure N.1: Flood map of 60 [mm/h] intensity storm (duration: 2 hours) created in 3Di. A retarding basin at Isiolo airport has been modelled in this schematisation

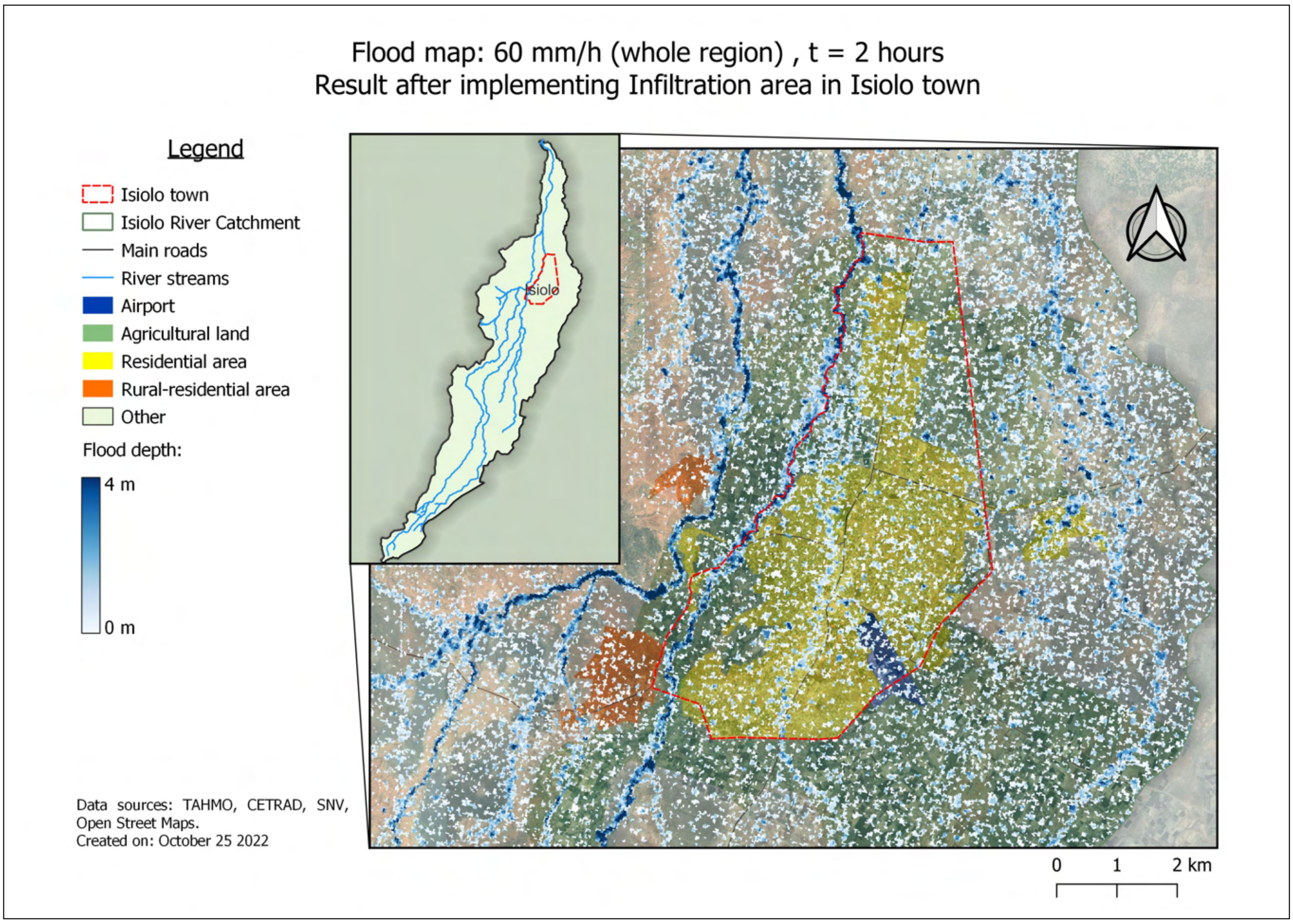

Figure N.2: Flood map of 60 [mm/h] intensity storm (duration: 2 hours) created in 3Di. An Infiltration area in Isiolo Town has been modelled in this schematisation

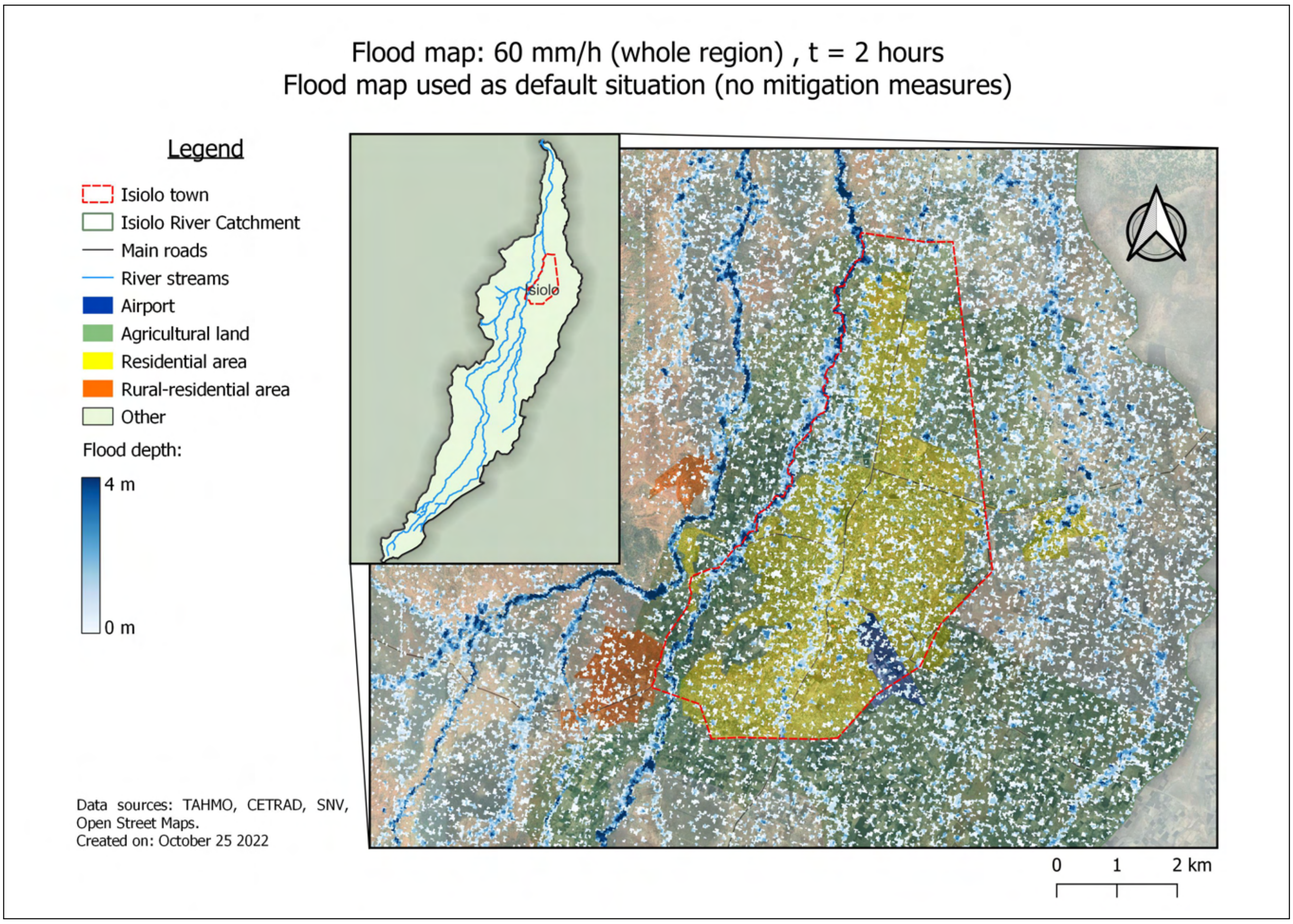

Figure N.3: Flood map of 60 [mm/h] intensity storm (duration: 2 hours) created in 3Di. Serves as a control map to compare results between different mitigation measures

Appendix O

Recommendations for improving the FIS Tool

This chapter focusses on providing feedback for usage of the FIS Tool, which Nelen & Schuurmans can use as a reference in the future to improve the development of the software. The following list consists of which we experienced could be looked into to make the user experience better, this is the result of interviews and conversations with interested stakeholders as well as our own input:

- If possible, adding a database on costs per type of mitigation measure per squared metre can give a direct indication of the net benefit of the mitigation measure. By specifying in the mitigation area definition it would be interesting to add mitigation measure information. In that way you can also get a result chart with the direct profit or loss for the mitigation measure. This would require long and extensive research to figure out for every mitigation measure but can really improve the user experience of the FIS Tool.
- In the scenario region definition, to edit the previously drafted region, it is expected that that already drawn points can be moved. If a square area definition is drawn, it is noticeable that if the bottom left corner point needs to be adjusted, it is required to delete the following two points before being able to edit the desired point. This means even though the previous points were drawn as desired, they would need to be drawn again if you want to edit the previous point. It would also be desirable to be able to upload a shapefile as the region boundaries, to make sure in every new project the assessed area remains the same.
- There is no documentation available on where the population data is gathered from. It would be interesting for the users to know how this data is acquired. The same goes for other data sets input into the software such as the land cover and the damage curves. A more in depth description can provide the users a clear image as to how the computations are done.
- When inputting a mitigation measure, it is possible to assign a certain protection level. 8 metres means the mitigation measure protects against any type of floods where you assume that everything in that area stays dry. To prevent confusion, it would be useful to add an "infinite protection" button. Now it is only possible to input mitigation measures as 'barriers', but a mitigation measure such as a bioswale acts different than a flood barrier. An idea to implement this is to be able to select areas in which the water level is reduced by 1 metre for example or a specific volume rather than a water depth.
- For some cases it seems that the before and after slides of population and flood damages. There are regions where the flood damages are mitigated but there is still an affected population in that protected area.
- The range of the water depth maps is not visible, so it is unclear to the user what each color means with regard to flood depth. Adding a colour bar can improve this experience.
- In the results page it could be useful to change the units of the currency as well as the units of the affected area. That way the users can best interpret the results to their local situation or purpose.
- Depending on the land cover of the satellite imagery, it can be difficult to interpret the before and after slides if the colors of the data match the background. Adding a possibility to change the colors could improve this experience.
- As far as we have experienced for flood maps in Kenya, the gender distribution charts do not seem realistic. If necessary to look at gender/age distribution of affected people, the population data should be updated.