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Sustainable Flood Management and Risk Reduction Action

Applicability of Nature-based Solutions for Flood and Drought Management in Somalia

Final Report

28 March 2022

Prepared for the Ministry of Energy and Water Resources of Somalia and the United Nations Environment Programme

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Prepared for: Ministry of Energy and Water Resources of Somalia
and United Nations Environment Programme

Prepared by: UNEP-DHI

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Executive Summary

The Ministry of Energy and Water Resources (MOEWR) in collaboration with the United Nations Environment Programme (UNEP) is carrying out the project “Sustainable Flood Management and Risk Reduction Action”, ongoing from August 2021 to March 2022. The project is funded by the Foreign, Commonwealth & Development Office (FCDO), which also included a component of implementing flood mitigation interventions carried out by the Food and Agriculture Organization of the United Nations (FAO).

The Somalia National Water Resource Strategy (NWRS) 2021- 2025, launched by MOEWR in April 2021, recognizes the importance that task forces and clusters have had as coordination and facilitation platforms in general, and for monitoring and reporting on flood and drought response, including humanitarian support resources. Furthermore, NWRS highlights the establishment of the National Flood and Drought Task Force as a key element for coordinating inter-ministerial responses. Alongside the importance of cooperative partnership with ministries at FGS and FMS levels, NWRS also focuses on building the capacity of institutions.

UNEP’s scope of work under this project includes activities designed to support the implementation of NWRS in the aforementioned aspects and the objectives laid out by FCDO, by supporting MOEWR with the following project objectives:

1. Data, information and tools to carry out flash flood risk assessment
2. Research on applicability of Nature-based Solutions (NbS) for flood and drought mitigation
3. Workshops for sharing of findings, collection of feedback and capacity-building.

This report documents the work pertaining to the second objective, with emphasis on flood mitigation. The data outputs of the project are available via the project online resource www.jubashabelle-tmo.org.This portal was used to disseminate findings during the workshop programme chaired by MOEWR. It has served as a key interface between the stakeholders and the project team.

Overview of the Approach

Many ephemeral rivers, or wadis, in Somalia are prone to flash floods, a type of flood is generated by heavy rainfall over a few hours, typically, resulting in a sudden increase in river flow followed by a quick recession. In turn, the severity and frequency of flooding from the Shabelle River has increased within the past few decades, particularly in the reach between Beledweyne and Jowhar, and it is stated that a major contributor to flooding is increased deposition and raising of the riverbed due to high sediment loads.

The project’s study areas are the flash flood prone wadis in the Beledweyne and Qardho areas, as well as, the Shabelle River stretch flowing through key urban centres from Beledweyne, Jalalaqsi, Bulo Burde, Mahaday, to Jowhar.

The first step was the identification of a list of tested NbS targeting flood (and in some instances drought) in the Somalia context. The key output of this work is the NbS catalogue. Secondly, a selection of the options with highest potential were examined in more depth using hydrologic and hydraulic mathematical modelling.

Finally, indicators for future prioritization of the most suitable NbS have been identified. Where present data is available, select indicator values have also been calculated. Priority has been given to indicators relating specifically to flood mitigation potential.

Definition of Nature-based Solutions within this Project

Nature-based Solutions (NbS) are approaches that involve a planned and deliberate use of ecosystem services to improve water quantity and quality and to increase resilience to climate change. In the context of this project, pure and hybrid NbS have been considered, the latter meaning that the solutions do not rely exclusively on ecosystem services to provide the expected benefits. “Hard” construction materials such as stones, wires, cement, etc. are used to establish the body of the structures. However, these can and have been used in combination with green measures such as revegetation and reforestation. Given their long record, basis in traditional knowledge, and use of locally available materials for establishment, these are considered to be highly important for upscaling of NbS applications.

Conclusions and Recommendations

Nature-based Solutions Catalogue

The research conducted to produce the project’s NbS Catalogue shows that a variety of NbS are applicable and have already been tested in Somalia. They have flood and drought management benefits, but also important co-benefits in most cases.

It was also important to consider “hybrid” NbS. Many of the recorded projects have utilized more than one NbS type, often in combination with other measures for resilience-building and humanitarian work. These can often address both floods and droughts (run-off capture and storage). They are based on traditional knowledge, tested and applied across the country, and considered locally acceptable. They involve locally available materials and allow local communities to be directly involved in installation and maintenance. Hybrid NbS are usually relatively low-cost, low-tech solutions, and present good opportunities for combining with green elements for additional benefit creation.

In summary, the catalogue presents a point of departure for the selection of NbS to be tested in the research activity, and captures other aspects such as the main challenges and key conditions for the success of NbS projects. These are summarized in Table 0.1.

Table 0.1 Key challenges and conditions for the success of NbS project implementations.

Key Challenges	Conditions for Success
Target groups not sufficiently consulted or involved in the planning processes, resulting in low motivation to engage in implementation and maintenance of NbS Insufficient site assessment causing malfunctioning (geology, topography, hydrology) Insufficient evaluation and management of sediment processes within the NbS, silt movement not managed leading to siltation, degradation problems Lack of catchment-level NbS planning, “moving” of the potential risks to other locations, creating risks of conflict Remoteness and conflict, leading to delays in implementation and abandonment of NbS structures Lack of proper maintenance (possibly due to lack of training of local actors), causing gradual degradation	Local awareness-raising and involvement in planning of NbS Livelihood motivation, creating opportunities to diversify livelihoods through NbS (startup and/or expansion of small-scale vegetable gardening, agroforestry) Local capacity for correct maintenance, training of local stakeholders to be able to undertake the necessary maintenance over time Local buy-in vital (e.g. where behavioral change is required) Selection of appropriate site, understanding the watershed-level dynamics, local soils, topography, etc. Watershed-level planning approaches to NbS projects Establishing arrangements and local governance structures for long-term maintenance

Nature-based Solutions for Flash Flood Mitigation

The aim of this research work was to assess the efficiency of the possible measures and provide recommendations on their potential use in Somalia. Models were set up to simulate the catchment response to heavy rainfall. The models could not be calibrated, as measurements of river flow were not available, so model parameters have been set based on experience from similar areas. For each area a baseline model was established and scenarios with the NbS in place were built, to enable comparison of the "before and after" conditions in terms of flood occurrence and impacts.

The results are not directly applicable for design of flood mitigation measures at these locations – local data would be required. The main purpose of the modelling has been to illustrate the differences between different kinds of measures and highlight some of the considerations that must be made.

Beledweyne is the capital of the Hiran Region in Hirshabelle State. The wadis surrounding the city represent a risk of flash floods. Hence, two wadis were selected to test possible solutions for this area: the Xarargagabaale and the Biifati. Qardho is the capital of Qardho District in Bari Region, Puntland State. Two wadis merge upstream of Qardho, making it prone to flash floods, with damage to infrastructure.

Next, a selected set of nature-based solutions (NbS) which can be applied to reduce peak flows were tested in a modelling environment to investigate possible catchment responses to implementation of the NbS. The summary of the findings is presented below.

Reforestation

Considerable deforestation has taken place in Somalia over recent decades. While reversing this trend can have many positive impacts, such as reduced erosion and CO_2 emissions, the focus of the current analysis is the potential impact on flash floods. It was found that replanting trees on 5 per cent of the area, corresponding to the loss of forest cover over the last 30 years, would have little impact on flash floods, reducing the floods peaks with only around 3%. Reforestation reduces flash flood potential by intercepting rainwater in canopy and the root zone.

Terracing

Soil loss due to erosion can often be reduced considerably by constructing terrasses along contours in the catchment area. This would also increase soil water infiltration, thereby supporting agricultural activities on the terraces. Terracing is one of the measures that may reduce and delay catchment runoff thus having the potential of reducing flood risk. It has been found that terracing, implemented for agricultural purposes, reduced the flash flood peak by around 10%.

Water retention

A weir built into the riverbank can allow the water to overflow when a water level critical for the downstream area is reached. The water would slowly return to the river through a drain at the lower end or be diverted for other purposes. This has been modelled in the Beledweyne study area for the existing, but currently not functional, Ceelgal Canal.

A sand dam, or similar small dams, across the river can help reduce flow velocities and temporarily store water in the river when inflow increases. This has been analysed in both study areas for different dam designs including sand dams, which are increasingly being applied in Somalia and similar regions to harvest rainwater.

Combined weirs are combinations of the sand dam and the v-shaped weirs. The bottom of the v-shaped opening has been raised by 1.5 m and 2 m, respectively, in two different scenarios. This holds back more water than the v-shaped weir, leading to more infiltration, while also being more efficient for flood peak reduction than the sand dam.

The main findings are:

- Small dams or weirs across the wadies can be applied to temporarily retain water and help distribute the flow over a longer time, thereby reducing the flood downstream.
- The most promising measure is V-shaped – or combined – weirs, which reduce floods by up to 60% in Qardho and up to 38% in Beledweyne. The results vary based on the size of the event, the season, and the area, but the v-shaped weirs show the potential can significantly reduce flood peaks and thereby reduce losses of lives and property in downstream settlements. The highest efficiency can be expected at locations where floods are particularly flashy, having high maximum flow values but limited total volume of run-off. A recommended way forward to implement measures of this type is given in section 7.1.

Detailed conclusions on flood peak reduction, aquifer recharge and the effect of the Ceelgal Canal can be found in section 3.4.

In addition to flood mitigation potential, the modelling exercise also investigated the potential for aquifer recharge. Table 0.1 presents the effects of the different measures on infiltration and water level. Sand dams have almost no effect on flood peaks (1% reduction compared to baseline). The opposite is true for V-shaped weirs (weirs (infiltration increase by estimated 23%), – an obvious trade-off situation. It is recommended that the design of structures consider the preferences of the local population and local potential for flash flood mitigation and increased water storage.

Table 0.2 The estimated daily infiltration along the Xarargagabaale River in the different scenarios, as well as the reduction of maximum discharge during the event of 28-10-2009. The infiltration is for the entire event of September-October 2009.

Scenario	Average infiltration [m^3/d]	Infiltration increase from baseline [%]	Flood peak reduction from baseline [%]
Baseline	240	0	0
V-shape	295	23	30
Sand dam	727	203	1
Combined 1.5 m	522	118	21
Combined 2 m	614	156	8

Nature-based Solutions for Shabelle River Flood Mitigation

It has been stated by different sources that a major contributor to flooding is increased sediment deposition in the Shabelle River. More frequent floods may destabilize riverbanks in itself, and another contributor to flooding can be bank collapse possibly caused or exacerbated by sediment erosion processes. These sediment transport processes in the upper Shabelle River in Somalia have been investigated using a 1D hydraulic river model with sediment transport components. Nature-based Solutions for bank stabilization and/or sediment load reduction can mitigate river flooding, hence in this project, scenarios for Nature-based Solution application have been investigated using the model.

Due to data limitations, the uncertainty of the model results is high. Therefore, exact numbers from specific locations have not been the emphasis of the results' analysis and presentation. Instead, the emphasis has been on determining the hydrodynamic and sediment trends and characteristic behaviours. Erosion is the detachment process of sediment particles from riverbeds and banks or land surface, whereas deposition is when sediment particles in the water column settle to the riverbed. The river flow conditions and sediment properties control whether erosion or deposition occur.

The baseline sediment transport model developed covers the Shabelle River from Beledweyne to Jowhar and indicates that the primary sediment process is deposition; the process most affecting the locations of bank overflows is also deposition, see Figure 0.1. While most locations along the river experience both erosion and deposition, 23% of the river is primarily eroding, and 77% is primarily depositing.

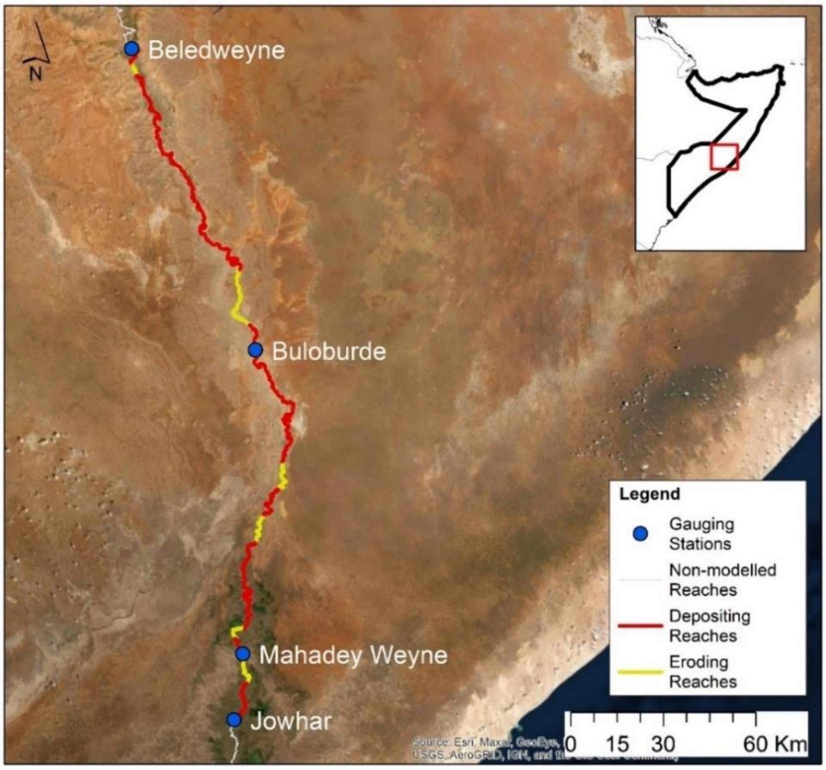

Figure 0.1 Depositing and eroding river reaches in the Shabelle river as identified from the baseline scenario.

Furthermore, when comparing with river breakage data (SWALIM FRRIMS, 2020) as seen in Figure 0.2, the overflow riverbank breakages are proportionately distributed between eroding and depositing river reaches, indicating that erosion is not an important process for riverbank collapse. The maximum resolution possible is 10-20 km stretches of river.

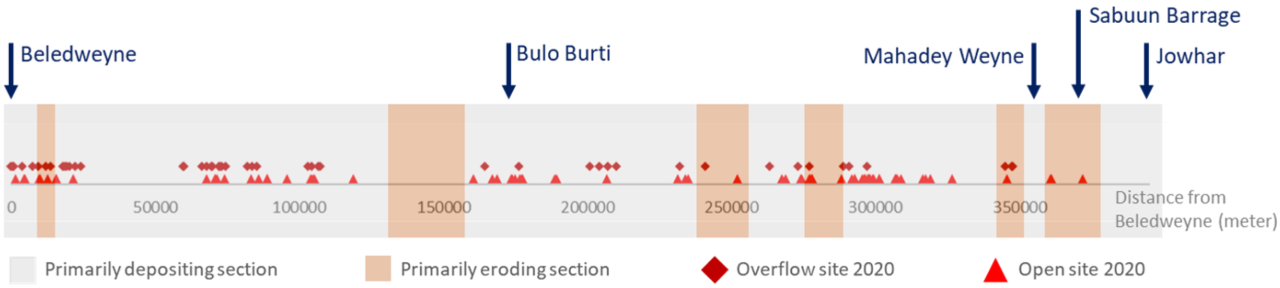

Figure 0.2 Location of eroding and depositing river reaches shown in profile (grey and brown coloured panels). Location of overflow and open sites from the FAO-SWALIM FRRIMS database for baseline year 2020.

NbS should focus on reducing the amount of sediment that enters the river to decrease deposition and reduce the incidence of sediment-related flooding. Scenarios to test these effects were modelled, and their results compared to the baseline simulation. Changes were made to the sediment boundaries in the baseline model setup to test NbS in three groups:

- Bank protection and stabilization efforts along the Shabelle in Somalia

- Reforestation/revegetation, implementation of sand dams, and gully protection of the Shabelle catchment in Somalia
- Reforestation/revegetation of the Shabelle catchment in Ethiopia

With the implementation of these three scenarios, it was possible to draw conclusions about the effectiveness of the application of NbS in decreasing the mass of sediment entering the river, in decreasing sediment deposition, and in decreasing the incidence of river flooding. When comparing the "before and after" conditions three measures were utilized: sediment mass balance, water level at Buloburde and bed level changes, the main findings are summarized below.

Bank protection and stabilization efforts along the Shabelle in Somalia

The total sediment that enters the system and that remains in the system as deposited sediment is 0.4 million tons less with NbS interventions for this scenario as compared to the baseline. 1.4 million tons remains deposited in the system during the baseline simulation, and 1.0 tons remains deposited in the system during the scenario. The bed level is on average 2.5-3.0 cm lower in the scenario than in the baseline, indicating that this is the amount of deposition prevented by application of the intervention for the five-year simulation period. The observed impact on water level at Buloburde shows that the number of days the river spills at Buloburde is reduced from 21 to 19.

Nature-based Solutions to stabilize riverbanks have many benefits not related to sediment load reduction, for example to ensure reliable use of the riverbanks as access ways / roads. There are local factors that inform bank stabilisation prioritisation, such as important infrastructure that requires protection or water intake pipes that could risk being silted up with sediment in the event of riverbank collapse. These results show that reduction of the incidence of river flooding is not a factor when selecting or prioritising where to implement Nature-based Solutions for riverbank stabilisation when considering the bigger picture, and rather that this important river management activity can be planned and executed based on other factors.

Reforestation/revegetation, implementation of sand dams, and gully protection of the Shabelle catchment in Somalia

The Nature-based Solutions selected that can reduce the sediment load added to the river due to topsoil erosion are those that either stabilize topsoil in the catchment and prevent erosion from occurring, such as reforestation and revegetation in the catchment, or that prevent eroded topsoil from entering the river, such as sand dams. Gully rehabilitation can work in both ways – sediment that would be eroded from the gullies remains in place, and topsoil eroded from the catchment can be retained in the gully vegetation. Three scenarios were tested for a five-year simulation period:

- "Maximum S. Topsoil Erosion Reduction," assumes perfect, ideal application, where all soil erosion from the catchment is prevented from entering the river (100% reduction). This is an extreme scenario that would be impossible to execute in reality; however, it is an enormously valuable modelling exercise, because much can be learned about how the Nature-based Solutions for topsoil erosion reduction in the Somali catchments impacts flooding.
- "Half S. Topsoil Erosion Reduction," simulates the situation where the topsoil entering the river is reduced by half (50% reduction).
- "Quarter S. Topsoil Erosion Reduction," simulates the situation where the topsoil entering the river is reduced by one quarter (25% reduction).

The total sediment that enters and that leaves the system is lower compared to the baseline in all three scenarios. In the Maximum S. Topsoil Erosion Reduction scenario, the incoming sediment is reduced by 3.15 million tons, which is only approximately one tenth of the total sediment load in the baseline scenario. However, more sediment exits the system in the Maximum S. Topsoil Erosion Reduction scenario than enters it. The system change in this scenario is negative, which indicates net erosion in the modelled system. In the Half and Quarter S. Topsoil Erosion Reduction scenarios, the amount of mass that remains in the system due to sediment deposition is 0.2 and 0.8 million tons, both much lower than the 1.4 million tons remaining in the baseline. The sediment mass balance results indicate that Nature-based Solutions for topsoil erosion reduction in the Somali catchment can substantially reduce the deposition of sediment in the Shabelle River.

The bed level is on average 20 cm lower in the Maximum scenario than in the baseline, 10 cm lower in the Half scenario than the baseline, and 5 cm lower in the Quarter scenario than the baseline. In the Maximum and Half S. Topsoil Erosion Reduction scenarios, the water level at Buloburde never reaches the bank elevation, which means that no flooding occurs. In the Quarter S. Topsoil Erosion Reduction scenario, there is flooding for 11 days, reduced from 21 days in the baseline.

The sediment mass balance and bed level elevation results show that the application of the Nature-based Solutions to reduce topsoil erosion in the Somali Shabelle catchment do substantially reduce deposition in the modelled domain. Data limitations prevent further analysis of how much eroded topsoil should be prevented from entering the river to achieve an acceptable flooding incidence reduction. Sediment deposition and erosion dynamics are highly dependent on the sediment grain size, and data on this key parameter is lacking. To obtain more detailed results, is it essential to collect information regarding the sediment grain size and bed composition along the length of the modelled domain and further refine the model.

Reforestation/revegetation of the Shabelle catchment in Ethiopia

The last Nature-based Solution scenarios tested are for topsoil erosion reduction in Ethiopia as a flood management intervention, and the same three levels of application were considered: “Maximum”, “Half” and “Quarter”. The total sediment that both enters and that leaves the system is lower compared to the baseline in all three scenarios. This indicates that substantial changes to the sediment load carried by the river at Beledweyne do not correlate to substantial changes in sediment deposition from the overall system perspective. Most of the changes in deposition between the three Ethiopian topsoil erosion reduction scenarios and the baseline occur within the first 100 km of the modelled domain. At Buloburde, there is very little change between the water level simulated in the baseline conditions and the three tested scenarios. If a location within the upper 100 km had been selected for comparison of flood incidence, it is likely that there would have been a difference in the flooding results.

These results are dependent upon the grain size of the modelled sediment particles. The silt and sand portions of the incoming sediment remain in suspension and travel through the model domain, while the sand portions of the incoming sediment deposit within the first 100 km. Grain size measurements of the suspended sediment and of the riverbed at Beledweyne are necessary to confirm the model results and are essential to any further refinements to the model.

Recommendations

Recommendations are listed in section 7.2, such as what data collection campaigns should be considered top priority. The established model has proven to be a useful tool for understanding some of the basic sediment-related mechanisms in the Shabelle River. As more data become available in the future, the model can be updated further and with a higher confidence be applied for additional purposes, such as a tool for prioritization of interventions and for informing flood risk with higher accuracy.

Impacts of Climate Change

To understand the impact of climate change on flood peak magnitude, infiltration and the mitigating impacts of NbS, climate change factors were calculated as an ensemble from nine different Global Climate Models, based on the IPCC AR6 projections, and applied to the baseline precipitation and PET timeseries in the hydrological models. A range of possible future scenarios, SSP1-2.6, SSP2-4.5 and SSP3-7.0, were selected to model climate change impacts in Somalia. In summary, rainfall is projected to increase in Beledweyne in the *Deyr* season in all three climate scenarios and in the *Gu* season in climate scenarios SSP1-2.6 and SSP2-4.5 but is projected to decrease in the *Gu* season in climate scenario SSP3-7.0.

The main finding of the climate change scenario modelling is that increased discharge leads to the NbS structures being less effective in reducing flash flood peaks. This may especially become an issue during the *Deyr* season which has high projected increases in all scenarios. It is found that increasing the width of the V's in the V-shaped weirs could make them more effective in high discharge events, although it is likely that it will reduce their effectiveness during events with lower discharge as a larger flow will be able to pass through unimpeded. It is recommended that wadis are assessed individually, with structures designed for events of specific magnitudes at locations where this type of structure is planned. It is generally recommended that climate change is considered when designing these structures.

Planning and Prioritization for Future Programming

A framework of indicators is proposed to guide the National Flood and Drought Task Force when planning and prioritizing NbS interventions. Detailed recommendations per indicator are listed in sections 6.1.1 and 6.2.1. These indicators are also proposed to UNEP and the international community for including in future development programming projects (overview in Figure 0.3). The key overall recommendation crucial for the success of NbS implementation is to collect information on metrics in relation to e.g., discharge, volume of water stored, soil erosion rates, sediment deposition, discharge volume and velocity. This is essential for measuring individual project success, but also provides vital insights into the scope for upscaling NbS at basin and country scale.

Indicator framework in support of NbS planning and prioritization

Placement	Hazard	Socioeconomics	Sustainability
Slope	Maximum flow/duration	Number of beneficiaries	Conflict risk
Soil type	Change in discharge	Vulnerability indicators	Community involvement: planning
Land use, land cover	Sediment deposition	[Land tenure]	Community involvement: implementation
[Invasive species]	NDVI	[Cost of implementation]	
Breakage points			
Flash flood indeces			

Figure 0.3 Example indicator framework for NbS planning and prioritization support, for the instances '[indicator]' no information is available.

Available datasets and next steps

The research outputs, namely, all data collected, and all data generated including model results, have been delivered to the MOEWR and the key datasets with the main findings (including project reports) have been uploaded to the portal for dissemination.

The conclusions and recommendations of this work have been discussed with the MOEWR and the National Flood and Drought Task Force in the final workshop held on the 28th of March 2022. The Ministry laid out an outlook for the future based on the recommendations. In the short term, the following needed actions were highlighted:

- Further data collection, field work, to improve the developed models and refine/improve risk reduction actions.

- Disseminate data collection recommendations of the research work, so that other projects that are ongoing in the field, can incorporate this into their workplans if possible.
- Targeted capacity building activities to support operation, transfer and maintenance of the tools developed under the FCDO project.
- More in-depth assessment of existing capacity and needs. Thematic areas identified during the current project include river hydraulics, sediment transport, water resources scenarios, and data management.
- Elaboration of a monitoring network for water flow and sediments: basic/best version depending on funding and accessibility/security at sites. The recommendations of the research work regarding top priority parameters to be collected should be followed.
- Institutional support to MOERW/National Task Force such as field visits, meetings, IT equipment, study tour, amongst others.

In the medium term:

- Selection of test sites for NbS option(s) – detailed monitoring is required to document costs/impacts and to develop proto-concept(s) – should be carried out in collaboration with NGOs already active in the respective locations and involved in risk reduction.
- Integration and streamlining of the proposed indicator framework into MOEWR project evaluation and monitoring processes (look to apply it already to any ongoing projects involving NbS implementation)
- Transboundary Water Allocation model for the entire Juba-Shabelle River System. As a point of departure, MOEWR is guiding a transboundary water resources study with UNEP support from March to May 2022. The study is a follow up activity of the FCDO supported research.
- Support to transboundary dialogue with Ethiopia in order to pave the way for the setting up of a transboundary institutional mechanism for cooperation.
- Support to establish joint monitoring program and transboundary data sharing protocols.

Finally, it is recommended that for sustainable application of this project's outcomes, the next step in the collaboration between MOEWR and UNEP is aimed at strengthening the capacity of the federal and state-level authorities. Via the project's workshop programme, requests by MOEWR and task force members have been put forward and relevant areas for development identified, and collaboration towards the development of a concept note is underway.

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List of Acronyms

AR5	Fixth Assessment Report (IPCC)
AR6	Sixth Assessment Report (IPCC)
CMIP6	Coupled Model Intercomparison Project Phase 6
DEM	Digital Elevation Model
EO	Earth Observation
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
FCDO	Foreign, Commonwealth & Development Office
FGS	Federal Government of Somalia
FMS	Federal Member State
GCM	Global Climate Model
GPM	Global Precipitation Mission
KAP	Knowledge Attitudes Practices
IGAD	Intergovernmental Authority on Development
ICPAC	IGAD Climate Prediction and Applications Centre
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
MOEWR	Ministry of Energy and Water Resources
MODIS	Moderate Resolution Imaging Spectroradiometer
NAM	Nedbør-AfstrømningsModel
NASA	National Aeronautics and Space Administration
NbS	Nature-based Solutions
NWRS	National Water Resource Strategy
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathway
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathway
SWALIM	Somalia Water and Land Information Management System
TMO	Transboundary Monitoring Observatory
UNEP	United Nations Environment Programme
UNFPA	United Nations Population Fund
UNICEF	United Nations International Children's Emergency Fund
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs
UNSOS	United Nations Support Office in Somalia
USGS	United States Geological Survey
WRM	Water Resources Management

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1 Introduction

The Ministry of Energy and Water Resources (MOEWR) in collaboration with the United Nations Environment Programme (UNEP) is carrying out the project “Sustainable Flood Management and Risk Reduction Action”, ongoing from August 2021 to March 2022. The project is funded by the Foreign, Commonwealth & Development Office (FCDO) of the Government of the United Kingdom via its International Climate Financing Water Resources Management (WRM) programme, which also included a component of implementing flood mitigation interventions carried out by the Food and Agriculture Organization of the United Nations (FAO).

The Somalia National Water Resource Strategy (NWRS) 2021- 2025, launched by the MOEWR in April 2021, is the key national policy instrument defining priority projects to address the identified main challenges to growth and development. Governance frameworks and corresponding policy, legal and regulatory instruments will, among other issues, be produced to address Disaster Risk Reduction (DRR), including flood and drought risk management. The NWRS recognizes the importance that task forces and clusters have had as coordination and facilitation platforms in general, and for monitoring and reporting on flood and drought response, including humanitarian support resources. Furthermore, the NWRS highlights the establishment of the National Flood and Drought Task Force as a key element for coordinating inter-ministerial responses. This is done under Sub-strategy 10 - Plan and responds to climate variability and its impacts on water resources management and development (adaptation, mitigation and recovery), Strategic Objective SO10b - Flood and drought risk management strategies and plans developed, Action A49 - Establish Permanent Flood Task Force/Committee to coordinate governmental action.

Alongside the importance of cooperative partnership with ministries at FGS and FMS levels, the importance of the task forces and clusters, and of strengthening governance and policy, the NWRS also focuses on building the capacity of institutions. Namely, under Sub-strategy 7: Undertake capacity-building & knowledge exchange interventions.

UNEP’s scope of work under this project includes activities designed to support the implementation of the NWRS in the aforementioned aspects and the objectives laid out by the FCDO. This will be achieved by producing research data and information and corresponding consultative and capacity-building workshops to support the FGS and the National Flood and Drought Task Force’s mandate. These activities will also benefit a broader range of stakeholders within the flood and drought management institutional framework in Somalia.

1.1 Objectives and Beneficiaries

UNEP, via its collaborating centre UNEP-DHI[1], is supporting the MOEWR with following project objectives:

1. Support government stakeholders with data, information and tools to carry out flash flood risk assessment
2. Research on applicability of Nature-based Solutions (NbS) for flood and drought mitigation
3. Workshops for sharing of findings, collection of feedback and capacity building.

The direct beneficiaries of the research findings are the National Flood and Drought Task Force, the existing State Flood Task Force members from Hirshabelle, Jubaland and South West States,

[1] UNEP-DHI Centre on Water and Environment is a UNEP centre of expertise, dedicated to improving the management, development and use of freshwater resources from local to global level, in operation since 1996. https://www.unepdhi.org/

decision-makers and planners regarding flood and drought mitigation/disaster management and, at a broader scale, Somali technical experts and stakeholders on flood and drought issues at federal and state level. The project's study areas are the Shabelle River Basin; the Shabelle River stretch in Hirshabelle State flowing through key urban centres from Beledweyne, Jalalaqsi, Bulo Burde, Mahaday, to Jowhar; and Qardho, in Puntland State.

1.2 Overview of the Approach

The first step in the assessment of the applicability of Nature-based Solutions (NbS) to Somalia's conditions was the identification of a list of tested NbS targeting flood (and in some instances drought) in Somalia context. The key output of this work is the NbS catalogue.

Secondly, a selection of the options with highest potential were examined in more depth using hydrologic and hydraulic mathematical modelling.

There is particular interest in assessing the potential of reforestation as a flood mitigation intervention, but also the impact of sand dams and terracing on especially flash flood mitigation is of interest. Hence these options have been investigated in the study. In addition, due to the general knowledge that sediment plays a role in the occurrence of floods in the Shabelle River, bank stabilization measures have also been investigated as NbS options for targeting sediments.

Finally, indicators for future prioritization of most suitable NbS have been identified. Where present data is available, select indicator values have also been calculated. The priority has been given to indicators relating specifically to the flood mitigation potential.

1.3 Purpose of this Report

This report documents the work pertaining to the second objective to research the applicability of NbS for flood and drought mitigation, with focus placed on flood mitigation. The report thus describes the work made related to the NbS Catalogue, the NbS options testing using hydrological and hydraulic models, and the development of NbS indicator system for prioritization of options. The data outputs of the project are available via the project online resource www.jubashabelle-tmo.org.This portal was used to disseminate findings during the workshop programme chaired by the MOEWR. It has served as a key interface between the stakeholders and the project team.

2 Nature-based Solutions Catalogue

A Nature-based Solutions (NbS) catalogue has been developed to support future planning for flood and drought mitigation by the Flood and Drought Task Force. The main objective of the catalogue development was to understand what NbS have been tested in Somalia to date and to assess their success in delivering benefits with relevance to flood and drought mitigation. This can then inform future development and upscaling of NbS projects in the basin and country. The catalogue is available for download at www.jubashabelle-tmo.org (from the 'Data Monitor' app).

The NbS catalogue development relied primarily on desk research. It contains a record of previous and current documented[2] NbS for flood and drought management, drawn from available research articles, reports and publicly available development project evaluation and assessment reports.

Focus has been on project applications in Somalia specifically, to capture NbS implementation experiences more broadly (including socioeconomic and governance aspects conditioning NbS implementation success). However, additional experiences from locations with a broadly comparable climate have also been included. Here focus was on capturing relevant solutions that have had limited (documented) application in Somalia specifically, to date.

2.1 Types of Interventions

The NbS types captured by the catalogue are included below.

Table 2.1 Description of types of Nature-based solutions included in the catalogue.

NbS	Primarily application purposes[3]
Agroforestry	Livelihood diversification, source of income for local populations
Balleys (ballies/ ballis)	Rainwater harvesting for livestock or human consumption, drought relief
Berkhads (establishment of rehabilitation)	Rainwater harvesting for livestock or human consumption, drought relief
Catchment conservation	Flood mitigation
Check dams	Water retention, flood mitigation, sediment yield reduction (sediment trapping)
Climate-smart agriculture	Mitigating floods, droughts, topsoil loss (preventing optimal water infiltration and water retention), water supply and increasing agricultural productivity.
Contour bunds (soil and stone bunds)	Prevention of surface water run-off, gully erosion, and surface sheet erosion, and rainwater harvesting for livestock
Farmer managed natural regeneration	Mitigation of soil erosion, and soil fertility loss, livelihood diversification
Gabions/gabion check dams	Surface water run-off control - flash flood mitigation, reducing erosion and preventing loss of productive agricultural land, prevention of gully formation
Grass strips	Runoff control and soil loss mitigation

[2] The NbS catalogue contains information on NbS project application and experiences that are currently documented, and documentation is publicly available. It is possible that additional NbS projects have been implemented in Somalia, which have not been captured given limited documentation availability for wider use.
[3] As stated in available documentation. Other benefits and purposes possible.

NbS	Primarily application purposes[3]
Gully rehabilitation/mitigation	Reduced runoff water speed, water diversion and infiltration facilitation for productive use (e.g. rangeland greening for cattle grazing)
Valley rehabilitation	Reduced land erosion and gully formation, benefits from the vegetation surrounding the gullies for livestock
Terracing/Integrated landscape management	Flood resilience building and ecosystem restoration, soil erosion reduction
Irrigation gates/gate rehabilitation	Restoring flood management infrastructure and irrigation facilitation for flood reduction
Reforestation	Ecosystem restoration and livelihood resilience, erosion prevention, reducing runoff/flood mitigation, combating land desertification
Revegetation (land-use change)	Stopping land degradation, providing food security, jobs and sources of income, runoff reduction and sediment yield reduction
Revegetation of gully banks	Gully bank stabilization and expansion mitigation
Riparian vegetation	Bank stabilization, flood mitigation
Riverbank erosion control and water harvesting structures	Flood management and mitigation
Sand dams	Reduced runoff water speed, water storage and improved infiltration, water for irrigation, potable water supply and to raise the level of shallow aquifers which supply adjacent shallow wells, greening of the surrounding areas for grazing, fruit production
Soil bunds	Reduced runoff water speed, water storage and improved infiltration
Subsurface dams/ water catchment dams	Rainwater harvesting for livestock and domestic use, livelihood benefits to pastoralists, regreening of surrounding areas in some sites
Water pond/earth dam (war/xurfad/balley)	Water for livestock, other productive uses

Many of the recorded projects have utilized more than one NbS type, often in combination with other measures for resilience building and humanitarian work (i.e. there are very few projects focusing on NbS alone - NbS have usually been included along with a variety of other activities). The records also point to NbS utilization primarily for addressing drought issue – thus for water capture and storage to provide water for human and livestock consumption. Many of the structures and approaches used are based on traditional methods – e.g. berkhads, gabions, earth dams, soil bunds.

A note here is made that many of the traditional water capture and storage structures fall under the ‘hybrid’ NbS type – meaning that the solutions do not rely exclusively on ecosystem services to provide the expected benefits. ‘Hard’ construction materials such as stones, wires, cement, etc. are used to establish the body of the structures. However, these can and have been used in combination with green measures such as revegetation and reforestation. Given their long record, basis in traditional knowledge and use of locally available materials for establishment, these are considered to be highly important for upscaling of NbS applications.

2.2 Successes and Challenges

2.2.1 Benefits

The record of NbS impact and efficiency in flood and drought hazard mitigation specifically is limited. This is partly due to the development project nature (the NbS installed and surveyed during project lifetime only which may be too short of a time span to observe any impacts) and party due to lack of systematic monitoring of the projects and their impacts on flood and droughts (e.g. where evidence is recorded, this is primarily anecdotic, not based on targeted indicator measurements).

From the projects in Somalia specifically, some evidence is available on the socioeconomic and hazard mitigation benefits from the NbS projects. These include the following examples from selected projects:

- Start-up and/or expansion of small-scale vegetable gardening, agroforestry, and other uses, and improvements in localized vegetation biomass (through construction of berkhads)
- Increased returns from dry land farming, improved water supply, enhanced knowledge and capacity of local ministries and NGOs on flood control and management (through catchment conservation)
- Soil erosion prevention and facilitating growth of vegetation for pastures (from check dam application, although specific metrics not recorded)
- Agricultural land gain as a result of the construction of gabions, also visibly prevented soil erosion and the extension of the gully into the agricultural areas.
- Gains for pastoralists and local communities alike, including enabling vegetable cultivation (from sand dam construction)
- Reduction in water price by 77%, on average (balleys for water capture and storage)
- A total of 17,500 cubic meters of water for livestock and other domestic uses made available to 5,000 families (through construction of 4 catchment dams)
- Increasing available water for household consumption by household consumption by 83% and the average time taken to fetch water decreased, from 3.5 hours to 20 minutes (balleys for water capture and storage)

For more information on the projects, please consult the catalogue itself which includes the attributes described in Table 2.2.

Table 2.2 Description of the catalogue.

Attributes	Description
Country	Country of NbS implementation.
Location	Specific location if available, locations outside Somalia captured where such examples are deemed comparable and relevant to the Somali setting.
Project	Project title.
Funding	Key funding/implementing organizations.
Year	The timeline of the implementation activities or project.
Description of NbS	Brief description of the intervention.
Scale	Where available, information on the scale of the NbS is captured eg area of forestation activities, volume of water stored, etc.
NbS primary purpose	The main purpose of the NbS recorded as described in the source documents. Many NbS relevant for flood and drought mitigation may have other intended purposes (eg ecosystem restoration), and these are also captured.
Other expected benefits	Any additional community and/or ecosystem benefits of the NbS are important to understand where investments in NbS might bring about most benefits.

Attributes	Description
Efficiency notes (flood/drought)	Where available, information relating to the NbS efficiency in mitigating flood and drought (where such events have occurred).
Challenges/notes of caution	Where available, information relating to any challenges regarding implementation, maintenance, or efficiency of the NbS are noted to account for aspects that may require special attention or mitigating measures.
Implementation notes	Record of any further notes specific to NbS performance efficiency to account for key learning experiences. These may include any innovative aspects relating to the NbS itself, implementation and governance arrangements, ways to improve efficiency, etc.
Source	Source documents identified as either 'research-' or 'project-based'. The catalogue aimed in particular to identify relevant documentation produced post-implementation to account for the full experience, including challenges and notes of caution. These included, for example, evaluation or review of reports on project activities by independent evaluators or academia. Research papers were also be included in the documentation, where aspects relating to specific NbS feasibility, location or efficiency are addressed in a detailed manner.
Research/development project	Type of project.
NbS type (Green/mixed/constructed community)	NbS based on ecosystem-service utilization are considered but the project included what can be considered "hybrid" approaches. Such approaches may include low-cost, low-technology solutions that utilize a mix of built and "green" elements. Such NbS may be particularly relevant for local conditions, if structures can be established using local materials and workforce and, importantly, also maintained by the local communities after project closure. This attribute marks "pure" NbS (e.g. reforestation) and "mixed" or hybrid solutions (e.g. gabions with vegetation).
Links	Source reference if available online.

Most NbS projects consider the socioeconomic benefits made available through these types of interventions, however it is also evident that the vast majority of projects do not undertake any systematic assessment and recording of these benefits, or importantly, the efficiency of the structures to deliver the desired flood and drought benefits (e.g. no records of decrease in flooding frequency, sediment reduction, reduction in flood velocities or discharge volumes).

2.2.2 Challenges in Efficiency and Maintenance

Lessons from previous NbS applications, as documented in the NbS catalogue, show that lack of appropriate site assessment and of a watershed-based approach to NbS planning, has previously caused suboptimal NbS efficiency or even complete NbS collapse. Examples of NbS performance issues due to insufficient site assessment include:

- Difficulty in successfully establishing NbS constructions (berkhads) due to hardness of the substrata.
- Soil bund performance issues, where the bunds were not constructed along the contours of the land terrain. The moderately undulating landscape caused uneven pressure on the bunds during rains, leading to cracks even with low amount of runoff.
- Insufficient evaluation, understanding and management of sediment processes within the NbS can significantly impede optimal functioning.
- Difficulties with gully revegetation activities and especially seedling establishment in gullies, where runoff discharge remained too high for the seedlings to be able to establish themselves.

- Lack of understanding of the dynamic evolution of the river systems after NbS interventions (e.g. the impacts of the established trees and vegetation on the flow, sediments and debris) and their impacts on flow conditions over time can cause new overflow situations.
- Lack of catchment-level impact assessment and NbS planning causing 'moving' of the potential risks to other locations, also increasing risk of conflict amongst landowners as the risks are simply shifted to other locations within the catchment.

Accounts on NbS efficiency and sustainability (primarily sourced from development project mid-term and terminal evaluation reports) also show that socio-economic factors have played a key role in the success and efficiency of the NbS in long term. Examples from past projects show how poor performance or NbS failure can be affected by various factors without direct relation to the NbS technical feasibility and efficiency alone. Examples include:

- Agroforestry projects where local awareness raising and involvement in planning were critical to the NbS success.
- In water reservoir (balley) projects, where target groups were not sufficiently consulted or involved in the planning processes, there was a low motivation to engage in the project or make contribution to the NbS establishment and maintenance.
- Remoteness and conflict presence has caused significant delays in implementation and abandonment of NbS structures (projects for water storage, balleys).
- In establishment of soil bunds, village involvement has helped increase success, with high level of community participation in implementation, including the training and deployment of village level surveyors.
- Farmer managed natural regeneration (FMNR) projects have shown that success is highly dependent on change in user behaviour (e.g. some areas might need to be closed off for cultivation or grazing), further highlighting the critical role of community engagement in planning and sustainability of NbS projects.
- In some sand dam projects, lack of proper maintenance (possibly due to lack of training of local actors) posed risk of erosion of the weirs and gradual degradation of the dam structures over time, already a relatively short time after project completion.

2.3 Species Information

For NbS projects involving restoration of ecosystems, but especially reforestation and revegetation activities, it is important to select the most appropriate species for the NbS purpose. Characteristics such as the root system density and depth, water requirements, height, leaf cover density, suitability for the local soils, etc., can be decisive in whether the species provide expected function in flood and drought hazard management.

Not all NbS projects provide detailed record of species used for the reforestation or revegetation activities. Where information is present, it does not always account for the success rates over time. The available information on species in the surveyed project documents is presented in the table below.

Table 2.3 Plant species information extracted from the catalogue.

NbS	Species information
Soil and stone bunds + gabions and check dams (Berbera, Sheikh (Saaxil region, Somaliland). Placement of lines of stones along the natural rises of a landscape, and contour farming.	- Project also introduced an improved variety of *forage grass (Mulatto II)* on 1,400 farms, primarily for fodder. - Forage grass *Brachiaria* – a relatively drought-resistant and durable plant with market potential, very simple to grow. It is suitable for

NbS	Species information
	cultivation in low-quality soil and has exceptionally high erosion-control potential.
Terracing/Integrated landscape management (locations in Somaliland and Puntland). Cash-for-work community-led soil and water conservation measures	Multipurpose and fruit trees, but no further species information.
Climate-smart agriculture, Southeast Kenya: Machakos, Makueni, and Kitui. Sustainable farming practices, including using drought-tolerant seed varieties and avoiding an overreliance on maize.	Native trees planted: a mix of species such as mango, citrus, acacia and many others.
Grass strips, Ethiopia, Jijiga Area, Northern Part of Somali Region. Grass strips as barrier against the runoff and soil loss.	Locally existing grass types in the region are desho, setaria (*Setaria anceps*) and vetiver (*Vetiveria zizanioides*). It is believed that desho grass belongs to *Pyppogamusae* family and Penispum genus, however its species is not identified yet.
Gully rehabilitation/mitigation/valley rehabilitation, Ethiopia in the Semien Gondar Zone, area in the northwestern Amhara region. Assessment of various gully rehabilitation methods to prevent soil erosion (including structural measures such as check dams and revegetation, Also in combination - e.g. loose stone check dam supported with green gold grasses).	Species present in the study area: barley with scattered tree species, such as *Cordia and Acacia*. Vegetative materials such as grass (*e.g., Chrysopogon zizanioides* (vetiver grass) and *green gold* and *elephant grass*) which can grow in a shallow soil with high tolerance to drought were utilized for erosion reduction.
Revegetation of gully banks, Ethiopia, Lake Tana Basin. Revegetation to increase soil stability and mitigate gully formation and expansion.	The potential natural vegetation of the area is the “evergreen Afromontane forest and grassland complex”. Historical reports indicate the commonest tree genus were *Acacia and Ficus* at lower elevations, and *Juniper* at higher elevations.

An assessment report on rainwater harvesting potential in Somalia, undertaken by SWALIM[4,] identifies the following species as suitable for improved rainwater management within the agroforestry systems. Recommendation is made to avoid selection of trees and shrubs with broad leaves trees they would mean higher evapotranspiration. Instead, it is recommended to select trees and shrubs that maximize reflectivity at the top canopy layer so that heat absorption is reduced to the minimum. Suggested target species, (particularly for top canopy hierarchy), are those with small pinnated leaves that quiver and cause air ventilation to the species in the lower canopy layers. Most of the Acacia and Ziziphus species, Pithecellobium dulce, Parkinsonia aculeate, Schinus molle, Salix subserata, Sclerocarya birrea, Moringa oleifera, Commiphora erythraea, Ximenia americana, Celtis africana, Balanites aegyptiaca, Boswellia rivae, Securidaca longepedunculaat, are noted to belong to this group.

SWALIM assessment also notes broader leaves which are aided either with thin film that covers the stomata of the leaves or have leathery leaves for reduced evapotranspiration, as a factor to consider. Sarcocephalus latifolius, Calotropis procera, Annona senegalensis, Celtis toka, Piliostigima thonningii, Agave Americana, etc., are few examples of such species.

[4] Potential of Rainwater Harvesting in Somalia: A Planning, Design, Implementation and Monitoring Framework, SWALIM (Somalia Water and Land Information Management), October 2007.

The assessment also notes that good understanding of the local hydro-physical features of the site, such as the prevailing wind direction and aspect, slope extent and orientation, amount of rainfall, soil depth and status of soil fertility of the site, are important factors. It is therefore recommended that a careful assessment of species suitability is done on a site-specific basis, taking into account these factors as well as flooding exposure and frequency (e.g. will the seedlings be able to establish themselves), slope, etc.

For example, if the land is shallow in soil depth, shrubs are preferred over trees. If the soil of the micro sites is weak in organic matter, deciduous trees and shrubs are more suitable. Revegetation or reforestation can also provide shade when it is practised along irrigation, thus minimizing evapotranspiration loss[5].

Project records surveyed also note that limiting grazing pressure, especially during the establishment phases of these projects, can be vital for success of the revegetation and reforestation projects.

Finally, native species are usually preferrable to ensure their suitability for the local conditions and minimize the risks of invasive species introduction. For example, the invasive plant Prosopis has done great damage by taking over arable areas. Widespread planting of Prosopis (a thorny, dominant and thirsty tree species) in Somalia took place in the 1980s as a response to deforestation. Since then, it has spread vigorously, invading at least 550,000 hectares in Somaliland alone[6]. Care must therefore be taken to ensure that species are suitable to local conditions and will not pose threat to local ecosystems.

[5] Potential of Rainwater Harvesting in Somalia: A Planning, Design, Implementation and Monitoring Framework, SWALIM (Somalia Water and Land Information Management), October 2007.
[6] FAO, 2020. Innovative ways of managing Prosopis juliflora trees in Somalia. https://www.fao.org/publications/card/en/c/CB0669EN/

3 Nature-based Solutions Targeting Flash Flood Mitigation

Many locations in Somalia are prone to flash floods caused mainly by Gu rainfall events, occurring between March and June, but also some years in the Deyr season from October to December. This type of flood is generated by heavy rainfall over a few hours, typically, resulting in a sudden increase in river flow followed by a quick recession.

This chapter describes analyses of possible nature-based solutions to mitigate flash floods. The aim is to assess the efficiency of the possible measures in general and provide recommendations on their potential use in Somalia.

The extent and severity of flooding has been reduced at many locations around the world through restoration of ecosystems, such as wetlands, and other ways of working with nature. These are methods that help to retain water in the catchment area or distribute the flood runoff over longer time, thereby reducing peak flow at vulnerable downstream locations.

Possible nature-based solutions (NbS) in Somalia which reduce peak flows include:

- Reforestation. The forested area in Somalia has declined for decades, causing increased soil erosion and reducing the retention of rainwater in the catchment area, thereby increasing runoff.
- Terracing. Catchment conservation measures, such as contour bunds, soil bunds, and terracing, can help retain and delay catchment runoff.
- Water retention. Sand dams, check dams and similar small structures in the rivers can temporarily store water and reduce downstream flooding.

These potential solutions have been assessed using hydrological and hydraulic models, simulating the catchment response to heavy rainfall before and after implementation of the proposed solutions.

3.1 Study Areas

Based on information on areas that are prone to flash floods, two study areas have been selected: wadis (ephemeral rivers) flowing toward the town of Qardho and wadis close to the town of Beledweyne. Lacking local data, the results are not directly applicable for design of flood mitigation measures at these locations. The main purpose of the modelling has been to illustrate the differences between different kinds of nature-based solutions and highlight some of the considerations that must be taken.

3.1.1 Beledweyne

Beledweyne is the capital of the Hiran Region in Hirshabelle State. It is located on the banks of the Shabelle River and has a history of flooding. Most of the wadis in the area do not enter the Shabelle River but dry up as they reach the flood plain, so flooding in the town is mainly driven by river discharge from Ethiopia. During extreme events, the discharge from the wadis will enter the Shabelle.

The data analyses done in this study indicate that the local contributions to flooding in the town generally appear as smaller peaks during a larger event driven by inflow from Ethiopia. An example of this is shown in Figure 3.1. There is a gradual increase in discharge in the river, caused by inflow from Ethiopia with a sharp peak around the 14th of October caused by local rainfall.

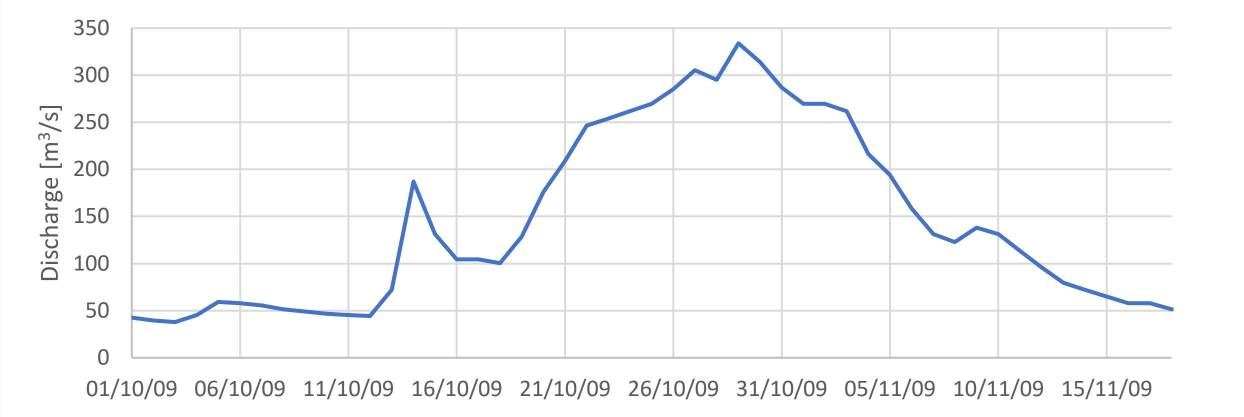


Figure 3.1 Discharge in the Shabelle River at Beledweyne during October 2009. The locally generated rainfall can be identified as the sharp peak around the 14 October.

An exception is an event in September 2012 which is unique in terms of the extreme amount of rain in the Beledweyne area. During this event, the local rainfall results in a sudden peak with very high discharge, see Figure 3.2.

Figure 3.2 Discharge in the Shabelle River at Beledweyne during an event in September 2012.

Generally, the locally generated discharge is expected to affect the discharge in Beledweyne Town as smaller, more sudden peaks during larger events. A more detailed analysis and calibration could determine the part of the flood that is generated locally. However, it is expected that the locally generated floods will mainly affect the wadis while Beledweyne Town will be more affected by water that is already in the Shabelle River.

In this section, the focus is on the flash floods in the wadis, and flooding in Beledweyne Town is not considered. Two wadis have been selected to test possible solutions, the Xarargagabaale and the Biifati. Similarly, to most other wadis in the area, these do not do not provide inflow to the Shabelle River. The Xarargagabaale is a tributary to the Biifati, which in turn reaches the Shabelle River flood plains upstream of Beledweyne Town, see Figure 3.3.

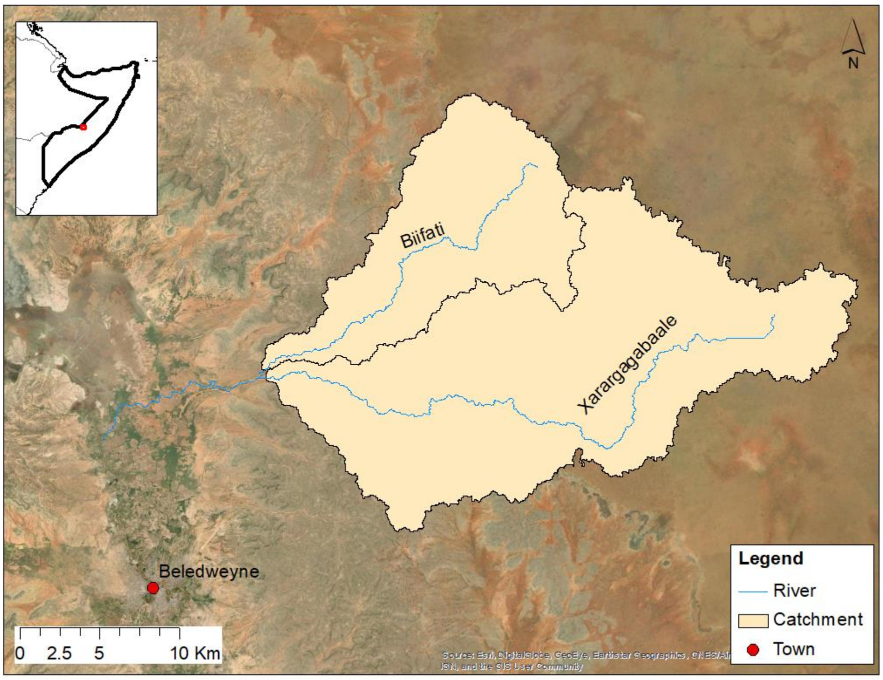


Figure 3.3 The two ephemeral rivers near Beledweyne that have been included in the modelling.

3.1.2 Qardho

Qardho is the capital of Qardho District in the Bari Region in Puntland State. Two wadis lead toward Qardho, merging upstream of the town. The rivers are prone to flash floods, causing damages in the town. An overview of the model area is shown in Figure 3.4. As in Beledweyne, the models cannot be used for design purposes, but only to illustrate the relative effect of different types of interventions.

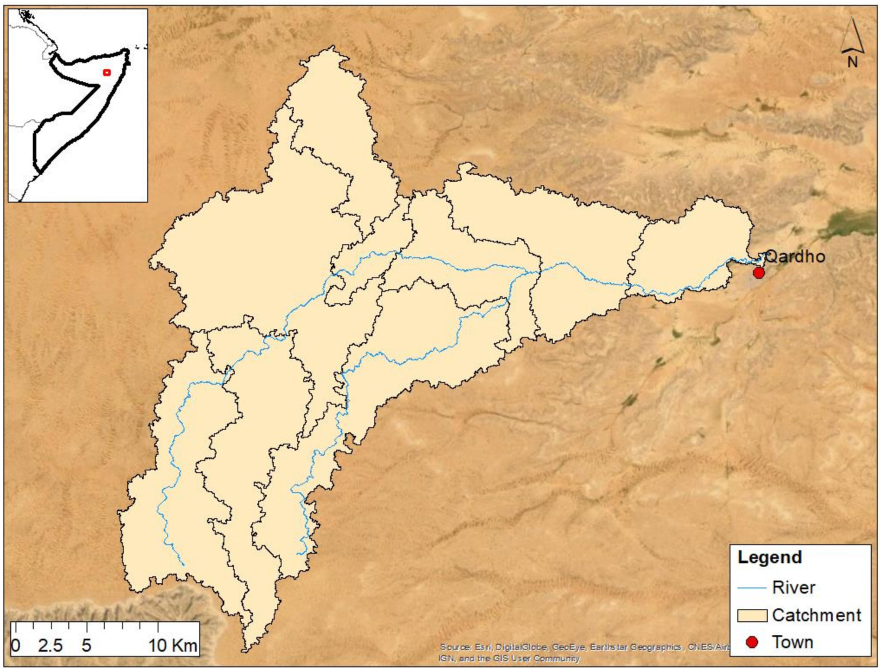


Figure 3.4 Qardho model area with rivers and sub-catchments

3.2 Nature-based Solutions Investigated

The approach to reducing flash floods in this study is using nature-based solutions. The background for the selected nature-based solutions is described in this section. For more details on how the solutions have been implemented in the models, see Section 3.4.

3.2.1 Water retention

Flash floods are characterised by high flow-peaks of short duration generated by heavy rainfall events. A temporary retention of part of the runoff can help distribute the flow over longer time and thereby reduce the maximum discharge value at critical downstream locations. The corresponding reduction in flood level and extent at downstream vulnerable locations can significantly reduce losses.

Flood water retention could be generated by:

- Deliberate flooding of a low-lying area, adjacent to the river, where the potential damage is limited compared to near-by or downstream vulnerable locations. A weir built into the riverbank can allow the water to overflow when a water level critical for the downstream area is reached. The water would slowly return to the river through a drain at the lower end or be diverted for other purposes. This requires identification of a suitable area, which has sufficient storage capacity and can safely be flooded from time to time.
- A sand dam or similar small dams across the river can help reduce flow velocities and temporarily store water in the river when inflow increases. This should preferably be applied at locations with limited slope of the riverbed, so a large amount of water can be stored upstream the dam. This storage would also locally cause increased infiltration to shallow groundwater, which can be used by the local population in the dry season.

The first option has been modelled in the Beledweyne study area for the existing, but currently not functional, Ceelgal Canal. The second option has been analysed in both study areas for different dam designs including sand dams, which are increasingly being applied in Somalia and similar regions to harvest rainwater. Sand is deposited upstream these dams over the first year or two after construction, so that water is mainly stored in sediment, reducing evaporation losses and the risk of bacteriological contamination. An example is shown in Figure 3.5.

Figure 3.5 Sand dam at Dinqaal community (photo Lopez-Rey, 2019).

3.2.2 Reforestation

Considerable deforestation has taken place in Somalia over recent decades. The current forest cover in Somalia is estimated at 9.4% of the country compared to 13% in 1990 according to the Global Forest Resources Assessment 2020 (FAO, 2020). This assessment shows that a general decrease in forested area has occurred over these 30 years. While reverting this trend can have many positive impacts, such as reduced erosion and CO_2 emission, the focus of the current analysis is on the potential impact on flash floods by reducing and delaying catchment runoff as rainfall is intercepted by the canopy and infiltrates the root zone.

3.2.3 Terracing

Soil loss due to erosion can often be reduced considerably by constructing terrasses along contours in the catchment area. This would also increase soil water infiltration, thereby supporting agricultural activities on the terraces. Terracing is one of the measures that may reduce and delay catchment runoff thus having the potential of reducing flood risk. Terracing would not be carried out for flood peak reduction alone, but this could be an added benefit when terracing the land for agricultural purposes.

3.3 Data Requirements and Model Setup

Models have been set up for the areas Qardho and Beledweyne. Because limited observed data were available, most model inputs are based on remote sensing data.

3.3.1 Modelling approach

For both study areas, the river modelling has been done in the MIKE HYDRO River software, where hydrological models have been set up in the sub-catchments while hydrodynamic models are set up in the rivers. The software allows the setting up of structures on the rivers as well as modifying the catchment parameters to reflect changes caused by e.g. reforestation. The modelling approach used to simulate the relationship between rainfall and runoff in the catchments is the NAM rainfall-runoff model (DHI, 2022).

The required data for the modelling are:

- Evaporation
- Precipitation
- Cross sections

The following sections describe the data inputs that have been used in the modelling, as well as the parameters for the NAM models. Finally, there is a brief description of the baseline models

3.3.2 Potential evaporation

The evaporation input to the models is MODIS PET (potential evapotranspiration), which is a satellite product from the NASA Earth Observations System project. It is measured with the Moderate Resolution Imaging Spectroradiometer (MODIS), which is the central sensor on board the Terra Satellite Platform. The PET dataset is estimated using Mu et al.'s improved ET algorithm (2011), which is based on the Penman-Monteith equation (Monteith, 1965) (University of Montana, 2021). The data is 8-daily, but for this project, the monthly mean is used. An example of MODIS data in the Juba-Shabelle basin is shown in Figure 3.6.

The evaporation is used both as an input to the rainfall-runoff model and to model evaporation along the rivers. In addition to the evaporation from the rivers, an infiltration of 1 mm/day has been assumed. While the evaporation in most parts of the river is expected to be negligible, but it may have a large impact on the storage in the temporary lakes behind the structures.

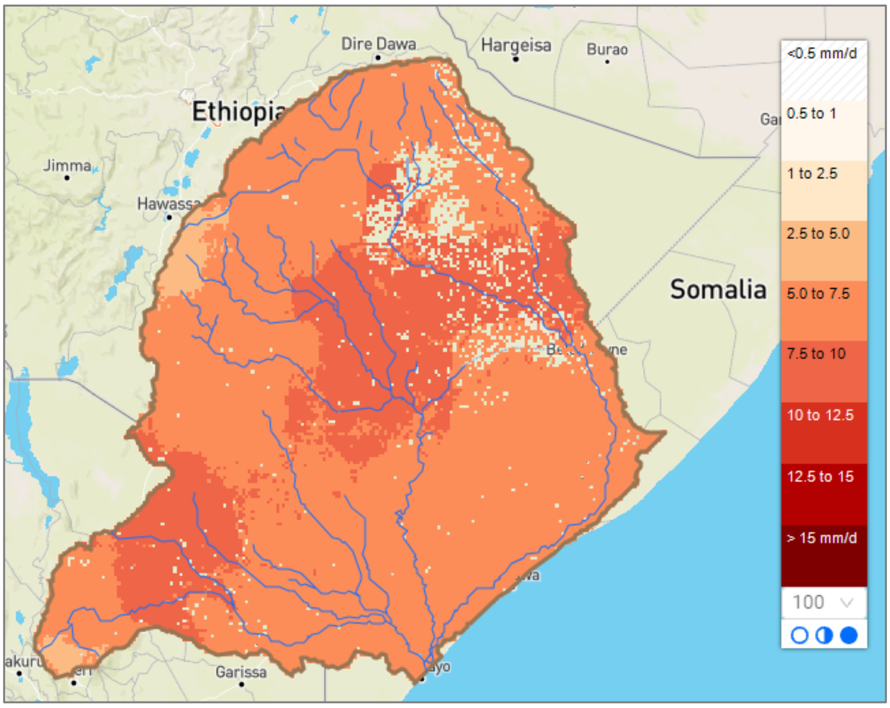


Figure 3.6 **Sample Potential Evapotranspiration (PET) data in mm per day for the Juba-Shabelle Basin, the source is MODIS by NASA**

3.3.3 Precipitation

Considering the flashiness of these floods it is important that the rainfall data applied in the models are of hourly or even finer temporal resolution. NASA's satellite-based rainfall data from the Global Precipitation Mission (GPM) provides rainfall data with a temporal resolution of 30 minutes, which is adequate for capturing flash floods. The spatial resolution is 0.1º and the data covers all parts of the catchment areas. The mission was initiated by NASA and the Japan Aerospace Exploration Agency (JAXA) (NASA, 2021).

While a temporal resolution of 30 minutes has been applied during high-rainfall events some of the rainfall input is using daily time steps in dryer periods.

3.3.4 Cross sections

There are no measured cross sections available for any of the rivers that have been modelled in this study. Instead, cross sections have been extracted from the SRTM 30 m DEM and adjusted to have a realistic shape. The cross sections have a spacing of some 4000 m on the main stretches of the river and 500 m upstream of the weirs. In the downstream end of the branches, where the DEM and images from Google Earth indicate that the flood plain begins, the cross sections are extended to a width of a few kilometres. This is done by extending the cross sections with straight lines without topographical features to avoid water being modelled in local depressions.

It should be stressed that the extraction of cross sections from the DEM is uncertain and that measured cross sections would be necessary for a model that could be used for design purposes.

3.3.5 Rainfall-runoff model

The NAM rainfall-runoff model is a deterministic, lumped, conceptual model which describes the rainfall-runoff processes occurring at catchment scale (DHI, 2022). The NAM model has been set up for the catchments in both model areas. No discharge data was available for calibration. Instead, the model parameters have been estimated based on experience from similar catchments, see Table 3.1, using somewhat different infiltration characteristics in the two areas.

Table 3.1 The parameters for the NAM rainfall-runoff models catchments in the two models. For each model, the parameters are the same for all catchments

	Parameter	Beledweyne	Qardho
Surface-rootzone	Maximum water content in surface storage (Umax)	10	5
	Maximum water content in root zone storage (Lmax)	100	30
	Overland flow runoff coefficient (CQOF)	0.8	0.8
	Time constant for routing interflow (CKIF)	500	1000
	Time constants for routing overland flow (CK1,2)	2	2
	Root zone threshold value for overland flow (TOF)	0	0
	Root zone threshold for interflow (TIF)	0	0
Groundwater	Root zone threshold for groundwater recharge (TG)	0.8	0
	Time constant for routing baseflow (CKBF)	2000	2000
	Ratio of groundwater area to catchment area (Carea)	1	1
	Specific yield of groundwater reservoir (Sy)	0.1	0.1
	Maximum groundwater depth causing baseflow (GWLBF0)	10	10

3.3.6 Baseline model

Different model versions are set up in both Qardho and Beledweyne: a baseline model, representing current conditions, and different scenarios in which one or more measures have been implemented. Although the uncalibrated models cannot be expected to describe the actual conditions accurately, the impact of the measures is expected to be reasonably well described, as simulations with and without these measures are made using the same model input and parameters.

In Beledweyne, a bridge has been located at Ceelgal Settlement based on Google Earth images (see Figure 3.7). This bridge is included in the model with dimensions estimated from Google Earth. This bridge is included in the baseline and all scenarios and is seen to have little impact on the flow.

Figure 3.7 Ceelgal Bridge. Image source and date: Google Earth, 22-05-2020.

3.4 Sand Dams and Other Structures

In both study areas, different structures have been tested to see their effect on flood peak reduction and water retention. The purpose of the structures is generally to retain water within the river, although the Ceelgal Canal in the Beledweyne area diverts water out of the main river when discharge is high. This section describes the structures that have been tested in Beledweyne and Qardho as well as the effect of the different structures.

3.4.1 Structures in Beledweyne

On Xarargagabaale, a cascade of two weirs has been modelled. On Biifati, the Ceelgal Canal has been tested. Figure 3.8 shows the locations of the different structures.

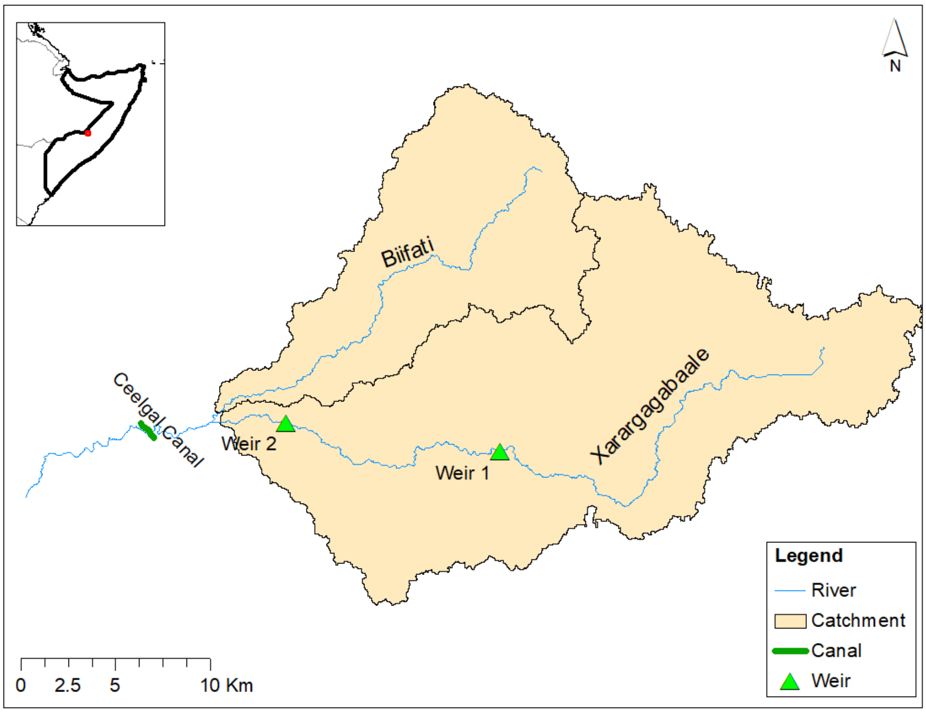


Figure 3.8 The structures that have been modelled in the Beledweyne model area.

Structures on Xarargagabaale

The structures on Xaragagabaale are inspired by sand dams, but modifications have been introduced in some scenarios to improve flood peak reduction. In all scenarios, Weir 1 and Weir 2 have similar dimensions. The following structures, illustrated in Figure 3.9, have been implemented:

1. Sand dams. A 3-metre-high, flat-topped structure that spans the river. Over time, sand will accumulate behind the structure.
2. V-shaped weirs. A structure similar to the sand dam, but with a v-shaped opening that starts at the riverbed level and reaches a width of 5 m at the top of the weir. This allows low flow to pass through, making the weir more efficient for flood peak reduction.
3. Combined weirs. These are combinations of the sand dam and the v-shaped weirs. The bottom of the v-shaped opening has been raised by 1.5 m and 2 m, respectively, in two different scenarios. This holds back more water than the v-shaped weir, leading to more infiltration, while also being more efficient for flood peak reduction than the sand dam.

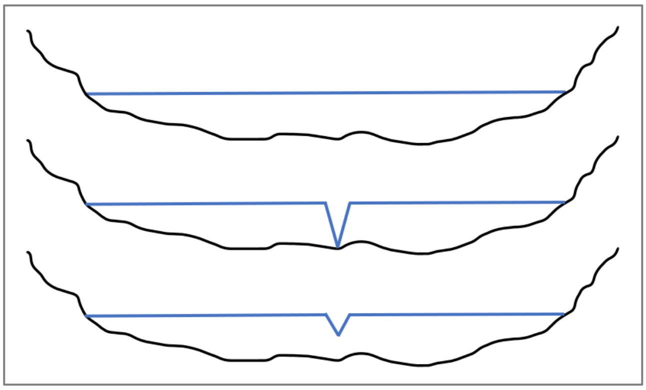


Figure 3.9 **While sand dams (top) block all flow for water levels below the crest level, the v-shaped weir (middle) lets some water flow through at all times. The combined weir (bottom) also includes a v-shaped, but smaller, opening.**

The structures have been placed in areas where the river upstream only has a gentle slope. This is to ensure the largest possible capacity for water storage. In areas where the river upstream is very steep, the area for storing water, and thus the effect of the structure, will be limited. The river profile and the locations of the two weirs are shown in Figure 3.10.

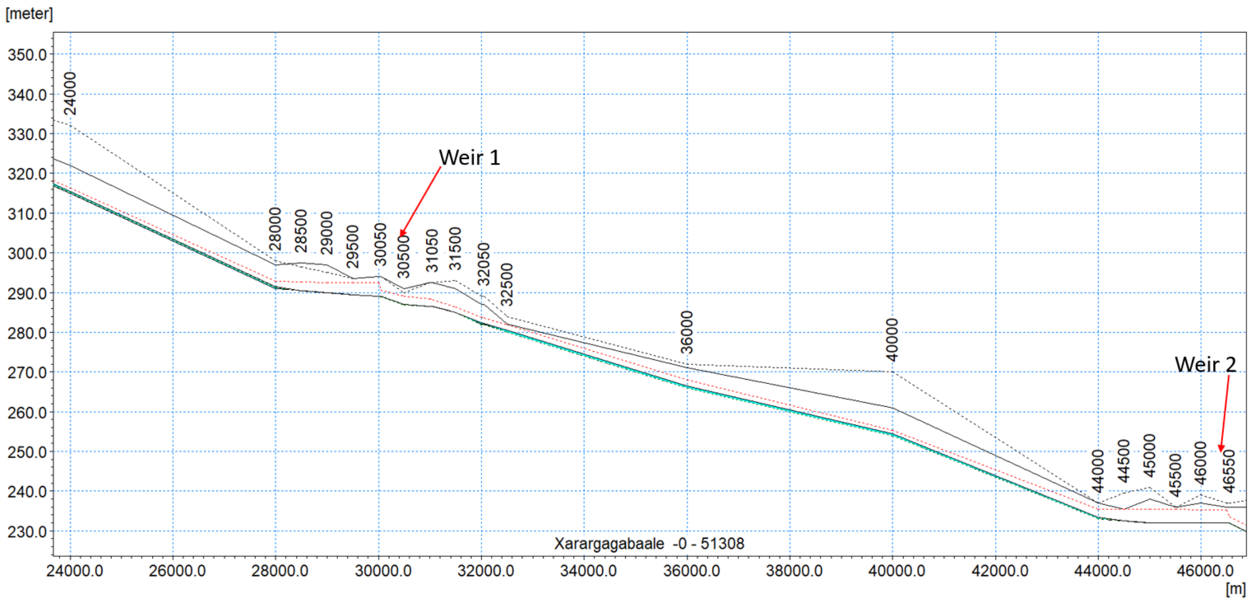


Figure 3.10 **Profile of Xarargagabaale and the location of the two weirs. Note how there is an area upstream of each weir with a moderate slope.**

Ceelgal Canal

The Ceelgal Canal is located just downstream of Ceelgal Settlement on the Biifati River. While its purpose is to provide water from the river for irrigation, it can also affect downstream floods. The canal is existing, but it is currently not functioning. It has been modelled as a canal with an approximate length of 1 km. The bed level in the upper end of the canal corresponds to the bed level in the river, while the lower end is assumed 2 m lower.

Water will spill from the river to the canal over a weir in the riverbank. Different hights of this weir have been tested, i.e. 0.5 m, 1 m, 1.5 m, and 2 m. The fate of the water once it leaves the main river is not modelled.

Figure 3.11 shows the location of the Ceelgal Canal. The settlement shown will not benefit from the flood reduction as it is located upstream the canal.

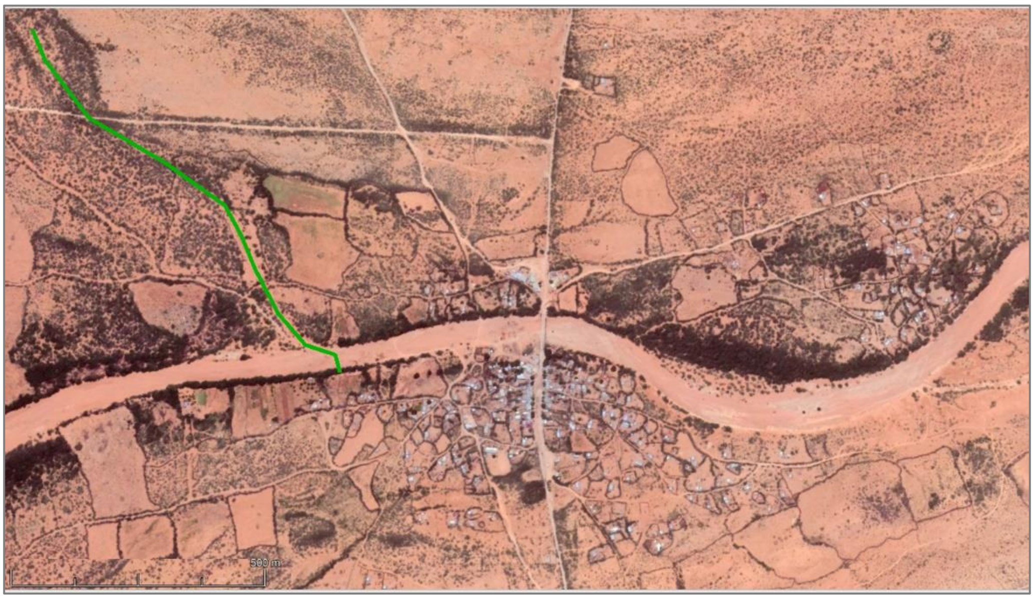


Figure 3.11 Location of Ceelgal Canal (green line). Note that it is located downstream of the settlement. Image source and date: Google Earth, 22-06-2020.

Discussion of Results

The section describes the effect of the structures on Xarargagabaale in the Beledweyne study area on both flash floods and aquifer recharge. The main focus is on September-October 2009 when where there were a number of flash floods with peak discharge exceeding the values of most years. The extreme event, which occurred in September 2012, has not been considered as the impact of small structures in the wadi on this would be negligible (see Figure 3.12). To show the effect of structures in different seasons, some scenarios have also been tested for an event in April-May 2016.

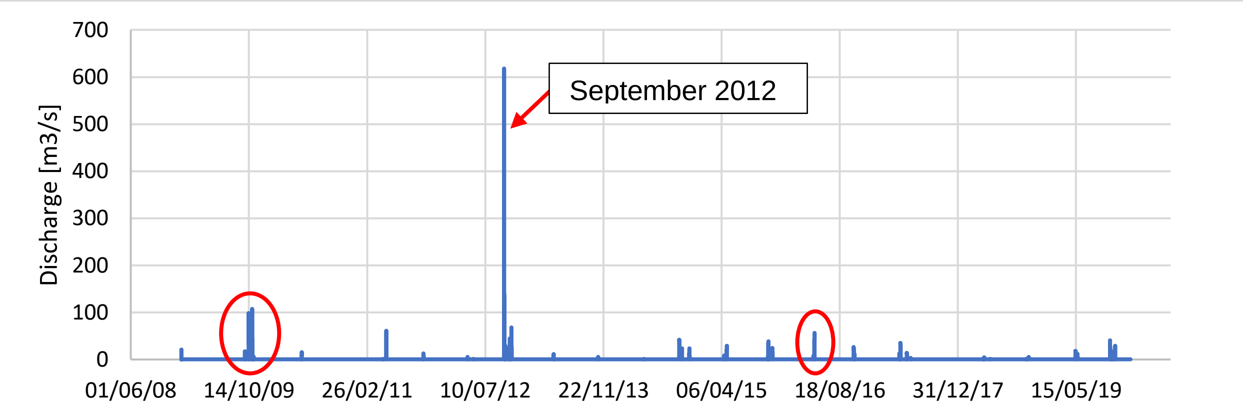


Figure 3.12 Discharge at the end of the Xarargagabaale branch. The selected events are marked with red circles.

Flood Peak Reduction

Figure 3.13 shows the discharge downstream of Weir 2 for the baseline and sand dam scenarios. The effect of the initial conditions in the weirs can be seen in the fact that the discharge of the first peak is clearly reduced compared to the baseline, while the sand dams have no effect on the subsequent peaks. The reason for this is that the lakes behind the sand dams are empty at the beginning of the rainy season and so the first flow event of the season is trapped behind the weir as the lake fills. In later events the lakes are already full, allowing the water flow to continue downstream unimpeded. Had the first peak of the season been higher, it is likely that the effect of the sand dam would have been smaller for this event as well.

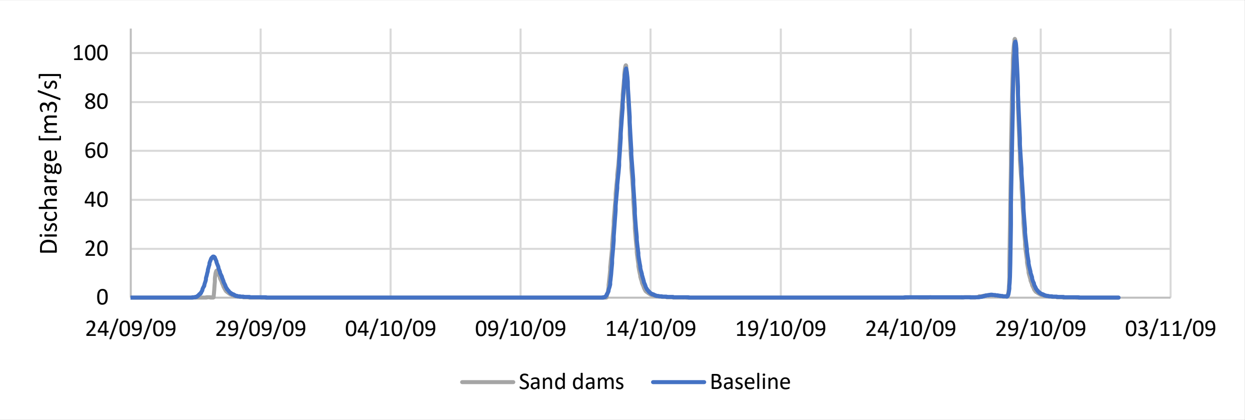


Figure 3.13 Discharge downstream of Weir 2 during September-October 2009. The sand dam scenario compared to current conditions.

The v-shaped weir has an opening that allows the low flow to pass through, meaning that it does not fill up in the same way as the flat-topped sand dam. The discharge downstream of Weir 2 for this scenario is shown in

Figure 3.14. The effect of these structures is clear, especially for the last peak in the end of October. The reason that the effect is limited for the second peak is most likely that there is a larger volume of water in this event.

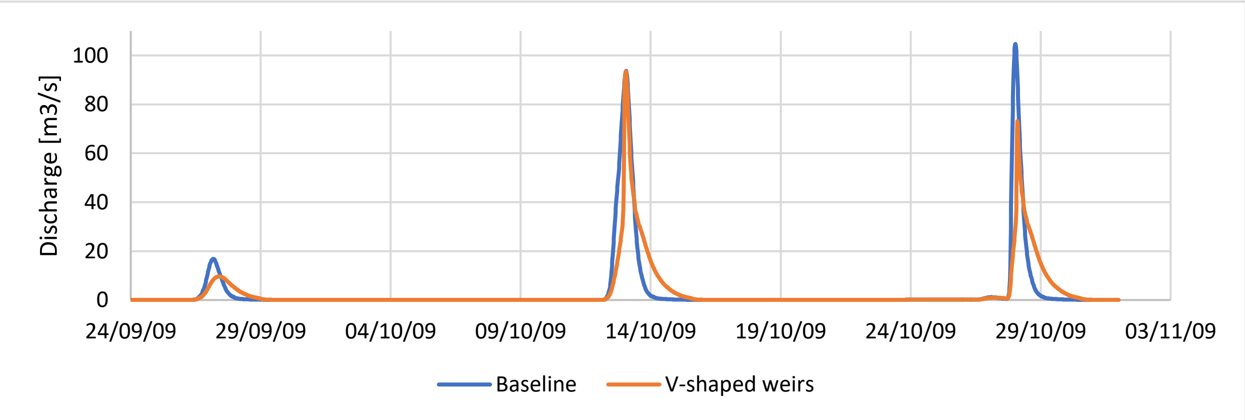


Figure 3.14 Discharge downstream of Weir 2 during September-October 2009. The v-shaped weir scenario compared to current conditions.

In Figure 3.15 the v-shaped weir is compared with the two combined weirs. In the first, small event of the season, the combined weirs perform best because they, similarly to what was seen for the sand dams, have capacity to fill up first. In later events they perform worse than the v-shaped weirs with regard to flood peak reduction. The reason for this that the temporary lake behind the weirs is full up to the bottom level of the v, resulting in a smaller capacity for retaining water.

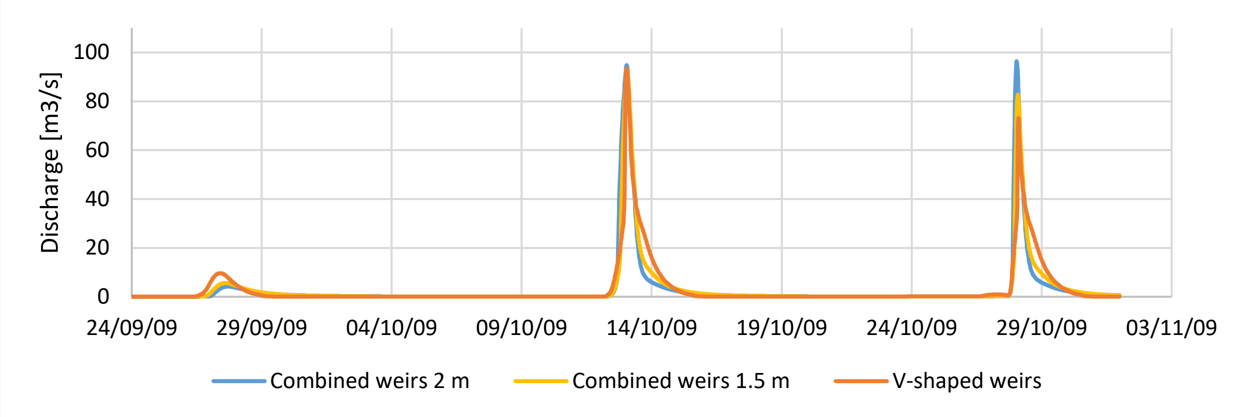


Figure 3.15 Discharge downstream of Weir 2 during September-October 2009. Comparison of the v-shaped weir scenario and the two combined weir scenarios.

The discharge downstream Weir 2 in April-May 2016 is shown in Figure 3.16 for the baseline, v-shaped weirs, and sand dams. The sand dams affect the first peak where they delay the peak, although the maximum discharge is approximately the same as the baseline. They have little effect on the second peak. The v-shaped weirs only reduce the first peak slightly but cause a significant reduction of the second peak.

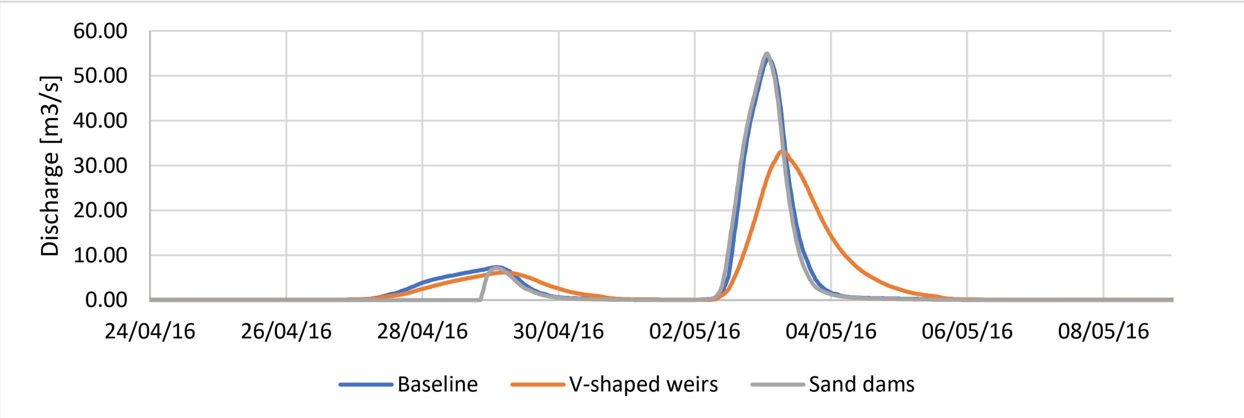


Figure 3.16 Discharge downstream Weir 2 during April-May 2016 for the baseline, v-shaped weirs, and sand dams.

Aquifer Recharge

Water is assumed to infiltrate with a rate of 1 mm/day. The aquifer recharge is then calculated by multiplying this value with the flooded area in the model, which varies with the river water level. The actual infiltration will depend on local conditions at each structure, but for the purpose of assessing the relative impact of different structure types on infiltration, this data is not required.

As a larger flooded area leads to more infiltration, the water level is obviously an important indicator for the amount of infiltration. Figure 3.17 and Figure 3.18 show the water level upstream of Weir 1 and Weir 2, respectively. The differences between the scenarios are very clear with the water level being at the crest level for the sand dams and at the bottom of the v-shaped opening for the combined weirs most of the time. The v-shaped weir scenario has water levels that are only slightly higher than the baseline during low flow. The infiltration would therefore be expected to be highest for the sand dam and lowest for the v-shaped weir, with the combined weirs distributed in between.

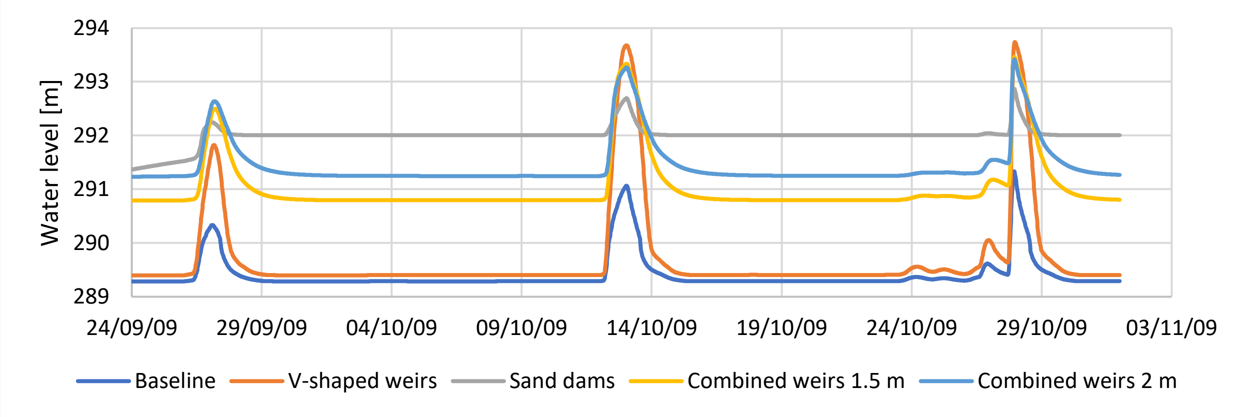


Figure 3.17 Water level upstream Weir 1 during September-October 2009.

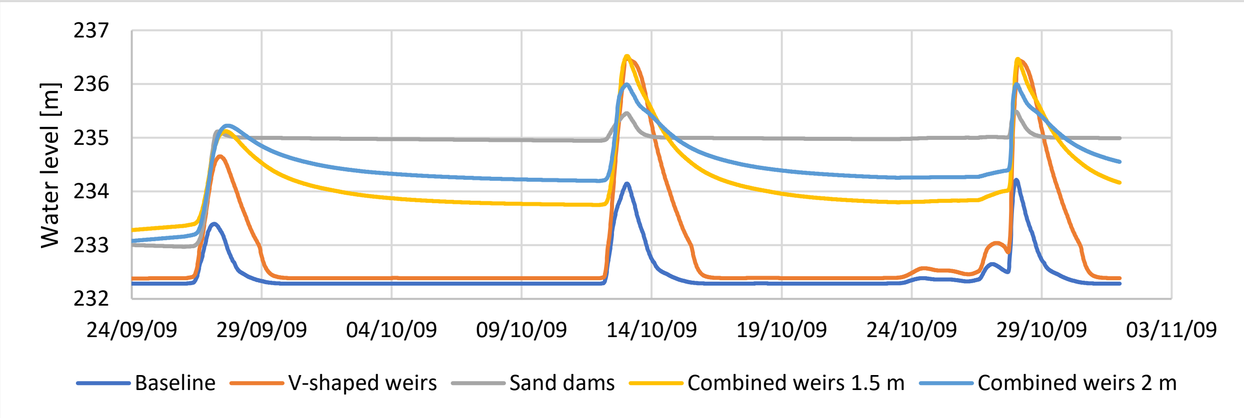


Figure 3.18 Water level upstream Weir 2 during September-October 2009.

The estimated average daily infiltration is shown in Table 3.2 along with the flood peak reduction. The differences are very clear, with the sand dams increasing infiltration by more than 200%, while the v-shaped weirs only increase infiltration by around 25%. The variation in infiltration for the different scenarios is clearly directly comparable to the variation in water level in the previous plots.

The previous section showed that the sand dams have almost no effect of the flood peaks, while there is a significant reduction for the v-shaped weirs. The trade-off is obvious, with poorer performance in flood peak reduction leading to more infiltration and vice versa. The design of structures should therefore be made considering the preferences of the local population and the local potential for flash flood mitigation and increased water storage.

Table 3.2 The estimated daily infiltration along the Xarargagabaale River in the different scenarios, as well as the reduction of maximum discharge during the event of 28-10-2009. The infiltration is for the entire event of September-October 2009.

Scenario	Average infiltration [m^3/d]	Infiltration increase from baseline [%]	Flood peak reduction from baseline [%]
Baseline	240	0	0
V-shape	295	23	30
Sand dam	727	203	1
Combined 1.5 m	522	118	21
Combined 2 m	614	156	8

Effect of Ceelgal Canal

The Ceelgal Canal is an alternative type of structure as it does not retain water in the river itself but diverts it and leads it away from the main river (Biifati). As the water is not modelled once it diverts into the canal, the effect of this structure on aquifer recharge cannot be estimated. However, given that this water is mainly diverted for irrigation purposes, it should be assumed that it will somehow be stored or used, although there are likely to be losses. Figure 3.16 shows the effect of the canal on the flood peak. The canal reduces the downstream flood peak, but does not have a significant effect, especially when considering that there is no critical infrastructure just downstream of the canal. The rehabilitation of the canal may have benefits for irrigation infrastructure, but it should not be done with the purpose of flood peak reduction.

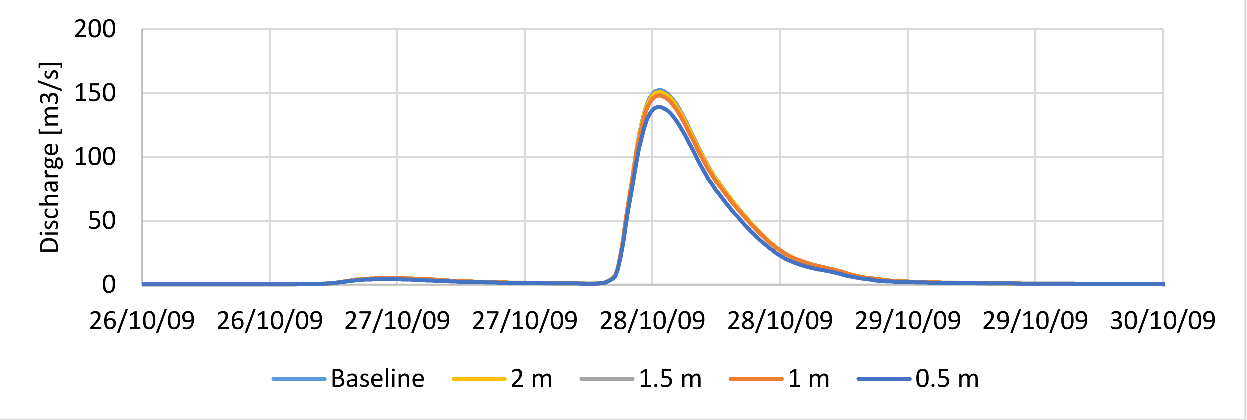


Figure 3.19 Flow downstream of the Ceelgal Canal for the baseline and for scenarios where the intake of the canal is in different heights.

3.4.2 Structures in Qardho

Four weirs have been introduced in the Qardho model, Weir A on the main river (northern river in Figure 3.20) and Weirs B, C, and D on the tributary (southern river).

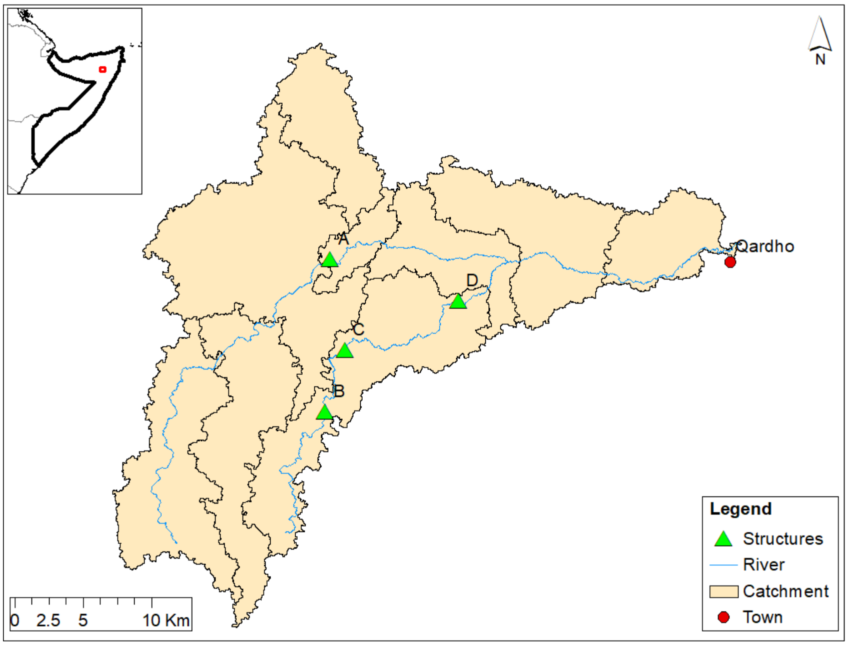


Figure 3.20 Location of the structures that have been implemented in Qardho.

Weir A has been placed at the end of a gently sloping stretch, where it would be possible to temporarily store a considerable amount of water (see Figure 3.21). There is not a similar, long stretch for Weirs B, C, and D, which have been placer at smaller, local stretches with a small slope (see Figure 3.22).

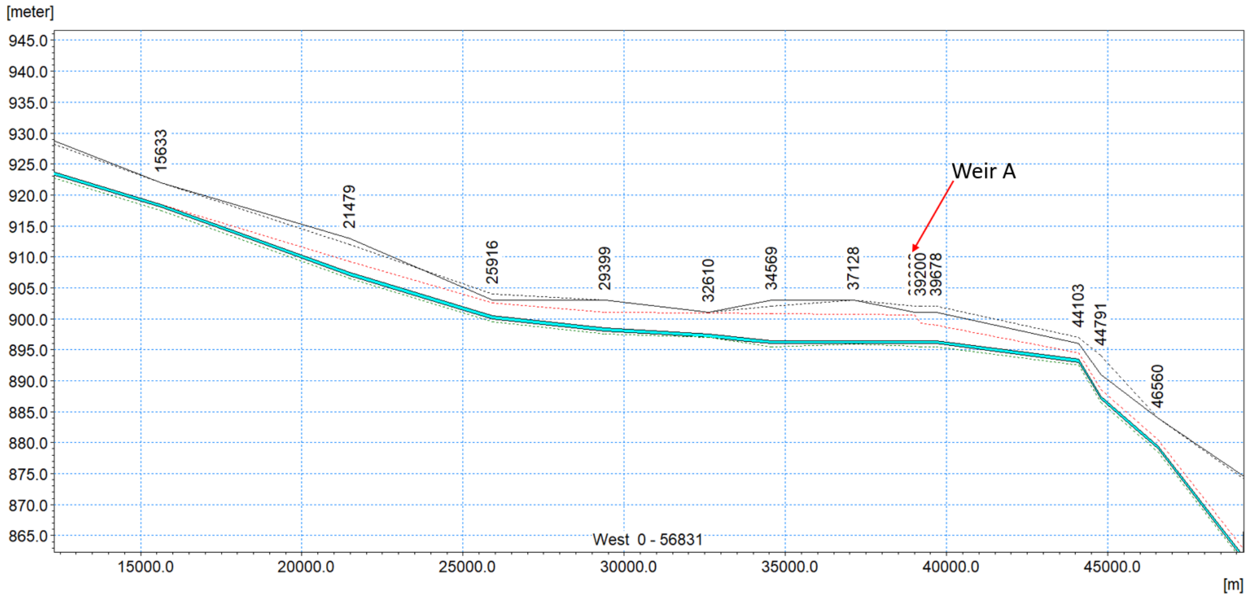


Figure 3.21 River longitudinal profile around Weir A.

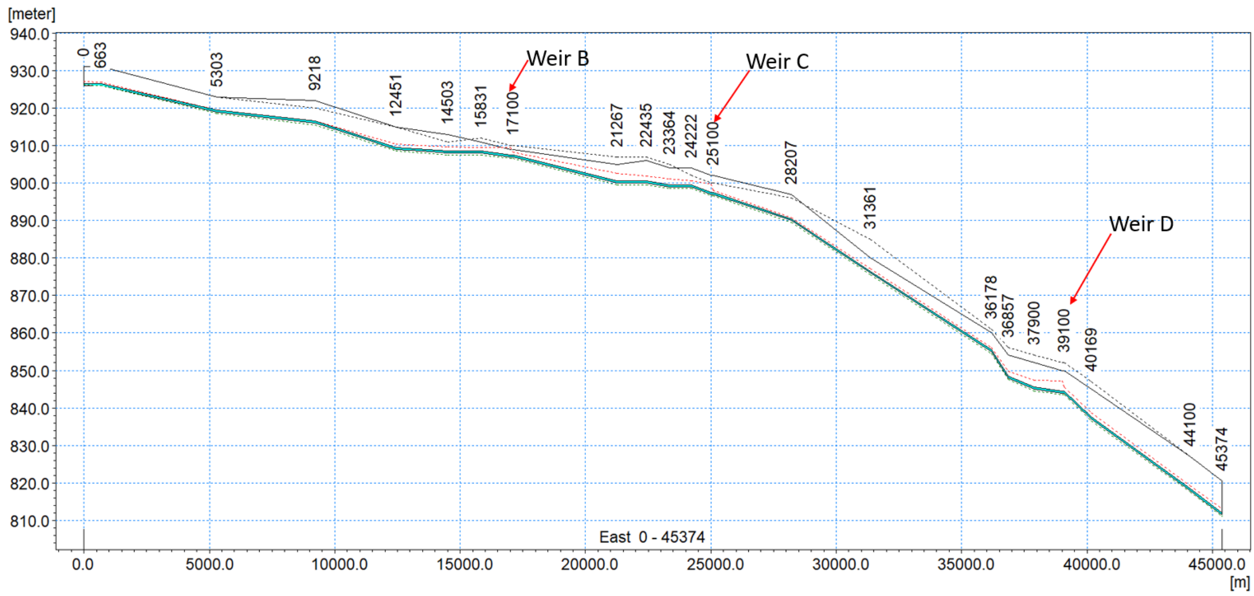


Figure 3.22 River longitudinal profile around weirs B, C, and D.

Four types of weirs have been tested, cf. Figure 3.9:

1. Empty sand dam: A recently constructed sand dam across the river, where the accumulation of sand has not yet started, so that the full upstream storage is available. The structure is 3 m high.

2. Filled sand dam: This represents the completed sand dam with sediments deposited up to the level of the weir.

3. V-shaped weir: A weir in which an opening has been introduced to allow low-flow to pass undisturbed and the temporary lake to be emptied relatively quickly to create storage for the next high-flow event.

4. Combined: A v-shaped weir where the bottom level of the v-shaped opening is raised 1.5 m over the bed level. In this scenario, only Weir A is combined, while the remaining three are v-shaped.

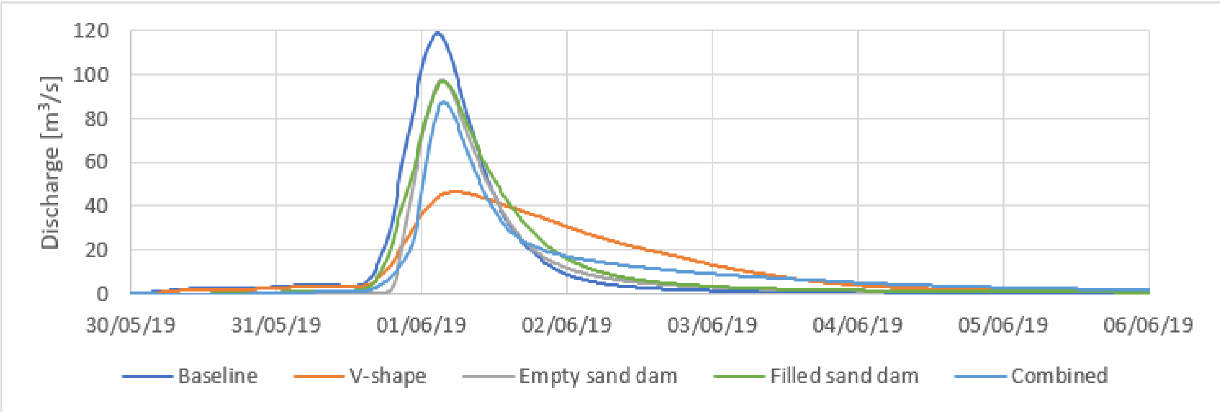
The weirs are tested in structure scenarios where all four weirs are the same type. The exception is the combined weir scenario, where only Weir A is combined and the remaining three weirs are v-shaped. The structure scenarios are compared to the baseline model without structures.

Discussion of Results

This section describes the impact of the structures described previously.

Flood Peak Reduction

The simulated impact of the different structure types in Qardho is illustrated in Figure 3.23 for Weir A, showing the discharge and water level variation at the weir during a flash flood event in early June 2019. As was seen in Beledweyne, the v-shaped weir has the largest effect. Unlike in Beledweyne, the sand dam also has a significant effect on the flood peak. The reason that this structure is more effective here than in Beledweyne is most likely that the lake upstream of Weir A has the potential of storing much larger amounts of water than the Beledweyne structures.



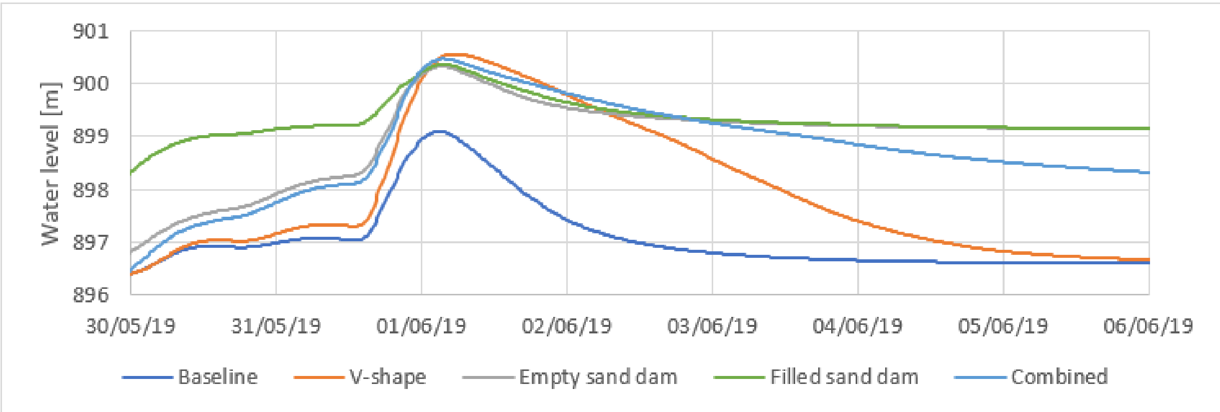


Figure 3.23 Simulated discharge just downstream Weir A (upper graph) and water level in the temporary lake (lower graph) for the five scenarios during a flash flood event.

The effect of the filled sand dam does not differ significantly from the empty sand dam at the peak. The combined weir reduces the flood peak compared to the sand dam, but not to the degree of the v-shaped weir. The effect of the structures here is generally higher than in Beledweyne for all types, which is most likely due to the size of the temporary lake.

The amount of stored water in the temporary lake will be high just after a high-flow event, thereby reducing the potential to retain water if another event occurs shortly after. This is illustrated in Figure 3.24 where the efficiency of the sand dam is seen to be low during the peak on 5th May 2011. The v-shaped weir functions well, however.

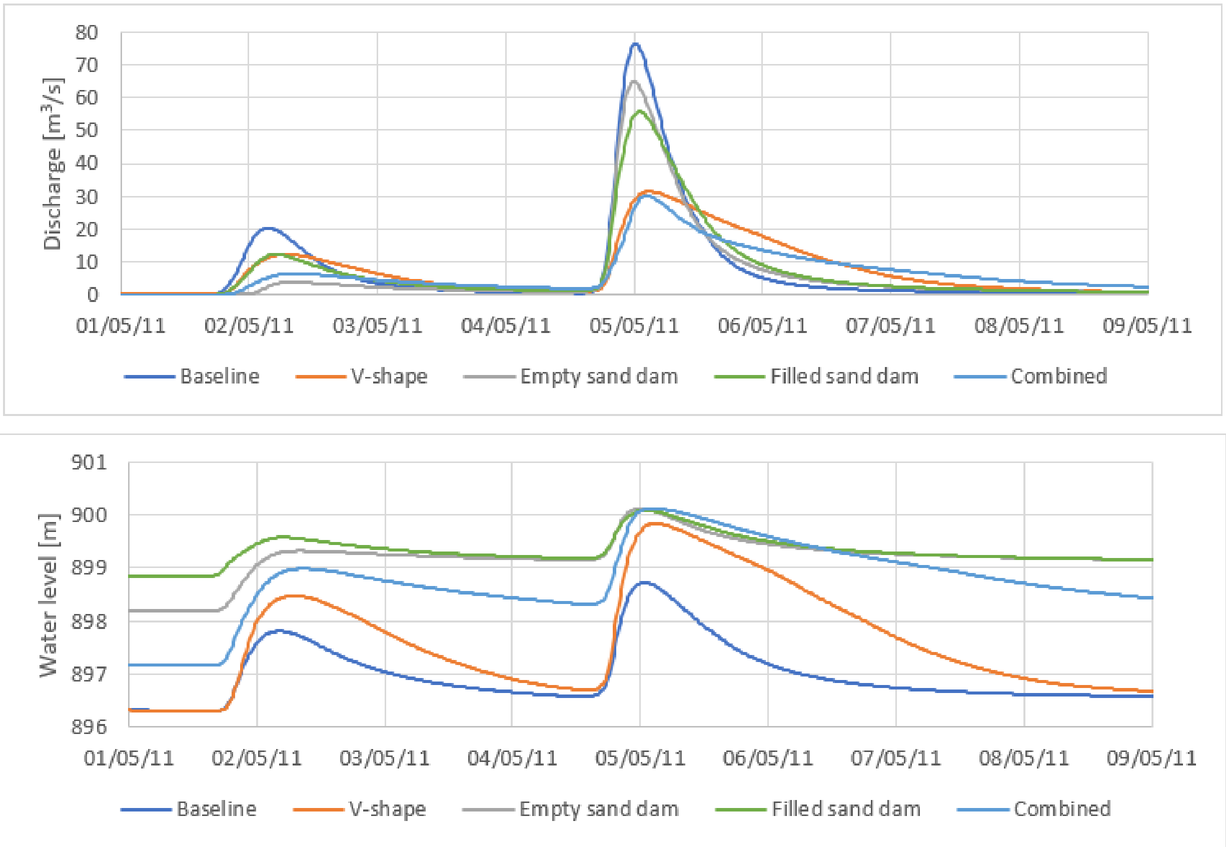


Figure 3.24 Simulated discharge just downstream the structure (upper graph) and water level in the temporary lake (lower graph) for the four scenarios during a double high-flow event.

Weirs B, C, and D are all on the tributary (the southern of the two rivers in Figure 3.20) at steeper locations, where the water storage possibilities are limited. The highest impact is obtained using v-shaped weirs, see Figure 3.25. As opposed to Beledweyne, the sand dam still has some effect on the flood peak reduction.

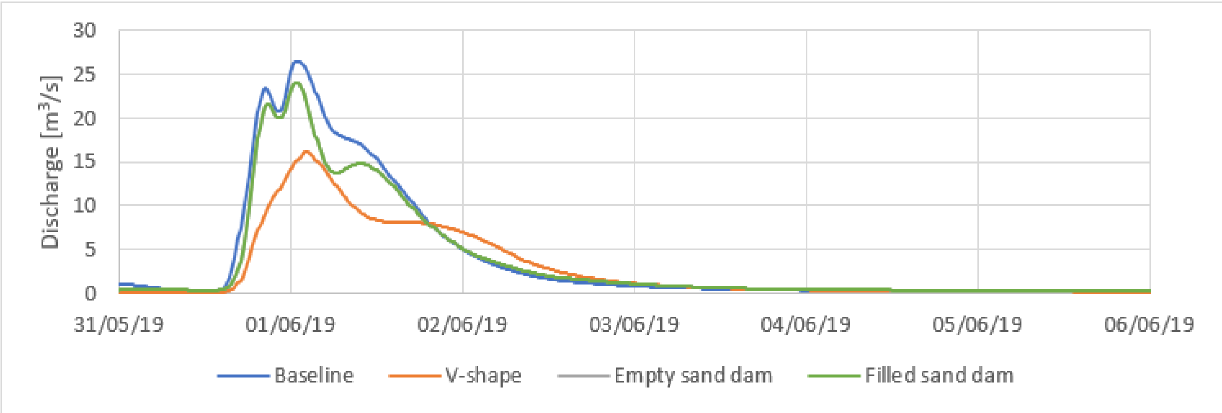


Figure 3.25 Tributary flow downstream the three weirs.

While a significant impact is obtained this test illustrates that the efficiency of flood mitigation measures of this type depends on the volume of water, which can be temporarily stored.

The combined impact of the different weirs/sand dams is illustrated in Figure 3.26, comparing the flow downstream the river confluence.

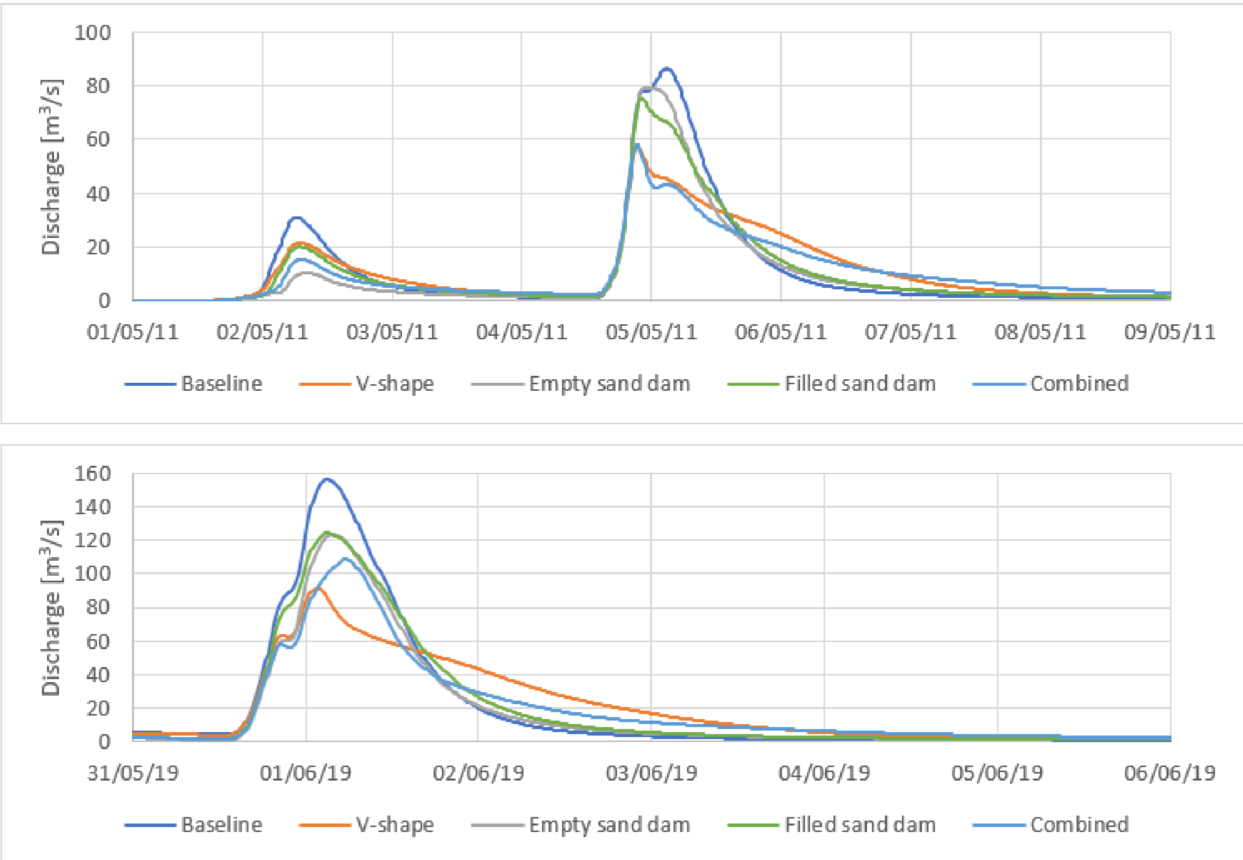


Figure 3.26 The flow downstream of the confluence between the tributary and the main weir, for the five scenarios in the two time periods that have been investigated: May 2011 (top) and June 2019 (bottom).

The obtained reduction in peak discharge in the different scenarios during the June 2019 event is shown in Table 3.3. It is seen that the v-shaped weir causes a reduction of the maximum flow at weir A to 39% of the original flood peak. Weir A is generally more efficient than the cascade of weirs on the tributary as the potential volume for temporary storage of water is considerably higher.

Table 3.3 The maximum discharge downstream the weirs in different scenarios during the June 2019 event.

Weir type	Flow downstream Weir A [m^3/s]	Percentage of baseline [%]	Flow downstream Weir D [m^3/s]	Percentage of baseline [%]
Baseline	118.76	100	26.41	100
V-shape	46.51	39	16.11	61
Empty sand dam	97.46	82	23.95	91
Filled sand dam	96.72	81	23.95	91
Combined	87.30	74	-	-

Aquifer Recharge

The infiltration is estimated in the same way as in Beledweyne with the assumption of an infiltration rate of 1 mm/day. To get results that were comparable to the ones in Beledweyne, the calculation has focussed on the infiltration at Weir A during April-May 2011. The estimated infiltration is shown in Table 3.4. The distribution is similar to the one in Beledweyne with the least infiltration in the v-shape scenario and the largest infiltration in the sand dam. The percentage increase for the sand dam is similar what was seen at Beledweyne. The infiltration from the empty and filled sand dams is roughly the same, but more water will be available once the sand dam is filled since it also stores water in the sand, where evaporation losses are limited.

Table 3.4 The estimated average daily infiltration for Weir A during the 2011 event.

	Infiltration [m^3/day]	Increase from baseline [%]
Baseline	555.12	0.00
V-shape	612.55	10.34
Sand dam	1635.76	194.67
Combined	943.82	70.02

3.5 Watershed Measures in Qardho

In addition to structures on the river, watershed measures have also been tested in the Qardho area. The measures in question are reforestation and terracing.

3.5.1 Reforestation

In the reforestation scenarios, 5% of the catchment area has been converted to forest, corresponding to conditions before 1990, the assumption being that the levels of deforestation in Qardho were broadly representative of the national change. The hydrological impact of this is simulated by significantly modifying the model parameters (see Table 3.5) for the reforested area only so that:

- The surface retention of rainfall due to canopy interception etc. is doubled

- The root zone storage is increased by a factor 4
- The distribution of excess rainfall between surface runoff and infiltration is changed from 20% of the excess rainfall going to infiltration to 40% of the excess rainfall going to infiltration, meaning that the amount of infiltration is doubled.

Table 3.5 The parameters that have been changed in the reforested scenario. Note that the changes have only been made in 5% of the catchment area.

	Parameter	Original	Reforested
Surface-rootzone	Maximum water content in surface storage (Umax)	5	10
	Maximum water content in root zone storage (Lmax)	30	120
	Overland flow runoff coefficient (CQOF)	0.8	0.6

3.5.2 Terracing

Assuming full vegetation cover on the terraces that are introduced in 25% of the catchment area, the impact of terracing on flash floods has been simulated by modifying the model as follows (see Table 3.6 for the changes in parameter values):

- The surface retention of rainfall is doubled as additional rainfall is required on the horizontal, vegetated terraces before runoff begins
- The root zone storage is increased by a factor 4
- The distribution of excess rainfall between surface runoff and infiltration is changed from 20% of the excess rainfall going to infiltration to 40% of the excess rainfall going to infiltration, meaning that the amount of infiltration is doubled.
- 10% increase in time of concentration as runoff is delayed in its initial path to the nearest stream

Table 3.6 The parameters that have been changed in the terracing scenario. Note that the changes have only been made in 25% of the catchment area.

	Parameter	Original	Terraced
Surface-rootzone	Maximum water content in surface storage (Umax)	5	10
	Maximum water content in root zone storage (Lmax)	30	120
	Overland flow runoff coefficient (CQOF)	0.8	0.6
	Time constants for routing overland flow (CK1,2)	2	2.2

3.5.3 Discussion of Results

The watershed measures that have been tested are reforestation and terracing as described in Section 3.3. These results are for the Qardho study area, and the model period is May 2010.

Reforestation

The impact of reforestation of 5% of the catchment area on the runoff has been calculated as shown in Figure 3.27.

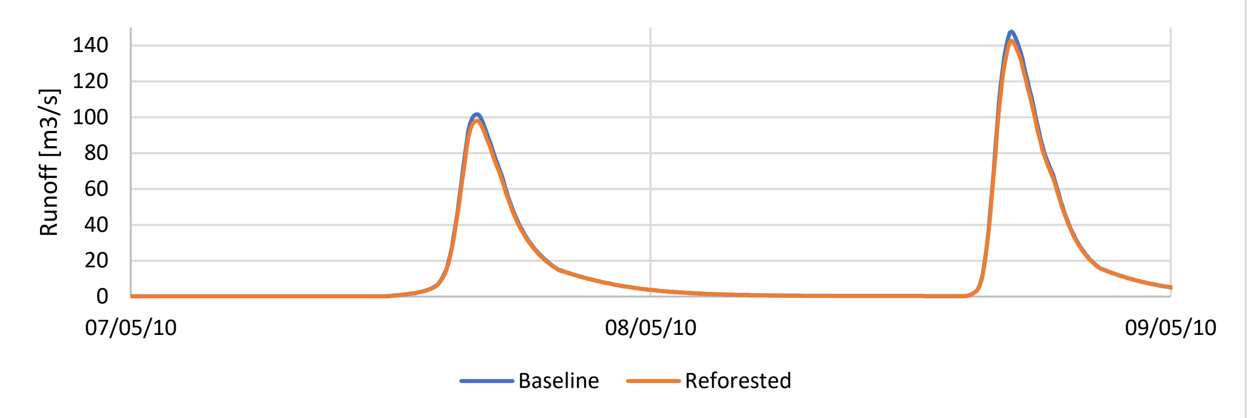


Figure 3.27 Simulated impact of reforestation in 5% of a catchment area.

The peak flow of the flash flood is seen to reduce, but only by a small percentage. This is due to the limited areal coverage of the reforestation and the somewhat limited impact that the forest has on very heavy rainfall events, as it is mainly the initial millimetres of rainfall that are retained.

Planting trees in a much larger part of the catchment area would help but may not be realistic considering the tree cover in Somalia over recent decades.

Terracing

The impact of terracing in 25% of the catchment area is illustrated in Figure 3.28. It is seen that the peak flow is reduced in both volume and maximum discharge. The reduction is not judged sufficient to justify terracing to this extent for flash flood mitigation only, but it could be seen as an added value if this is considered for agricultural purposes at suitable locations.

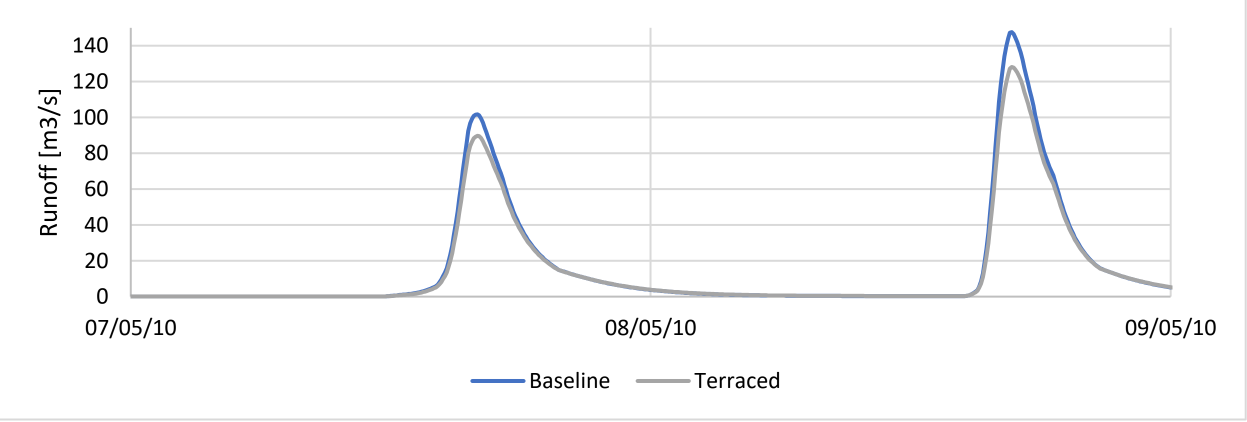


Figure 3.28 Simulated impact of terracing 25% of the catchment area.

3.6 Conclusions

Different ways of mitigating flash floods using nature-based solutions have been analysed for selected wadis in two study areas: near Beledweyne in Hirshabelle State and near Qardho in Puntland State. Local data on topography and meteorology have been applied.

Models were set up to simulate the catchment response to the heavy rainfall. The models could not be calibrated, as measurements of river flow were not available, so model parameters have been set based on experience from similar areas. The results can therefore not be applied for design of measures at the selected locations.

The main findings are:

- Re-planting of trees on 5% of the catchment area, corresponding to the loss of forest cover over the last 30 years, would have little impact on flash floods.
- Terracing, implemented for agricultural purposes, could contribute to reducing flash flood runoff.
- Small dams or weirs across the wadies can be applied to temporarily retain water and help distribute the flow over longer time, thereby reducing the flood downstream.
- A weir with a v-shaped opening was found to be the most efficient of the tested approaches for flash flood mitigation, while sand dams, which are made mainly to increase water availability in the dry season, has limited impact on flow peaks. Combined dams, with a smaller v-opening at the upper section of the dam, can reduce flood flow and increase infiltration to some extent.
- Weirs would be particularly efficient at gently sloping locations, where a considerable amount of water can be temporarily stored upstream.

The most promising measure is the v-shaped – or combined – weirs, which can significantly reduce flood peaks and thereby potentially reduce losses of lives and property at downstream settlements. The flood-impact of such structures will depend on the characteristics of the wadi where they are installed. The highest efficiency can be expected at locations where floods are particularly flashy, having high maximum flow values but limited total volume of runoff.

A recommended way forward to implement measures of this type is given in section 7.1.

4 Nature-based Solutions Targeting Sediment for Shabelle River Flood Mitigation

Within the past few decades, the severity and frequency of flooding from the Shabelle River has increased, particularly in the reach between Beledweyne and Jowhar (river reach shown in Figure 4.1). FAO-SWALIM states that a major contributor to flooding is increased deposition and raising of the riverbed due to high sediment loads (FAO-SWALIM, 2022). More frequent floods may destabilize banks in itself, and another contributor to flooding can be bank collapse possibly caused or exacerbated by sediment erosion processes. These sediment transport processes in the upper Shabelle River in Somalia have been investigated using a 1D hydraulic river model with sediment transport components. Nature-based Solutions for bank stabilization and/or sediment load reduction can mitigate river flooding, and scenarios for Nature-based Solution application have also been investigated using the model.

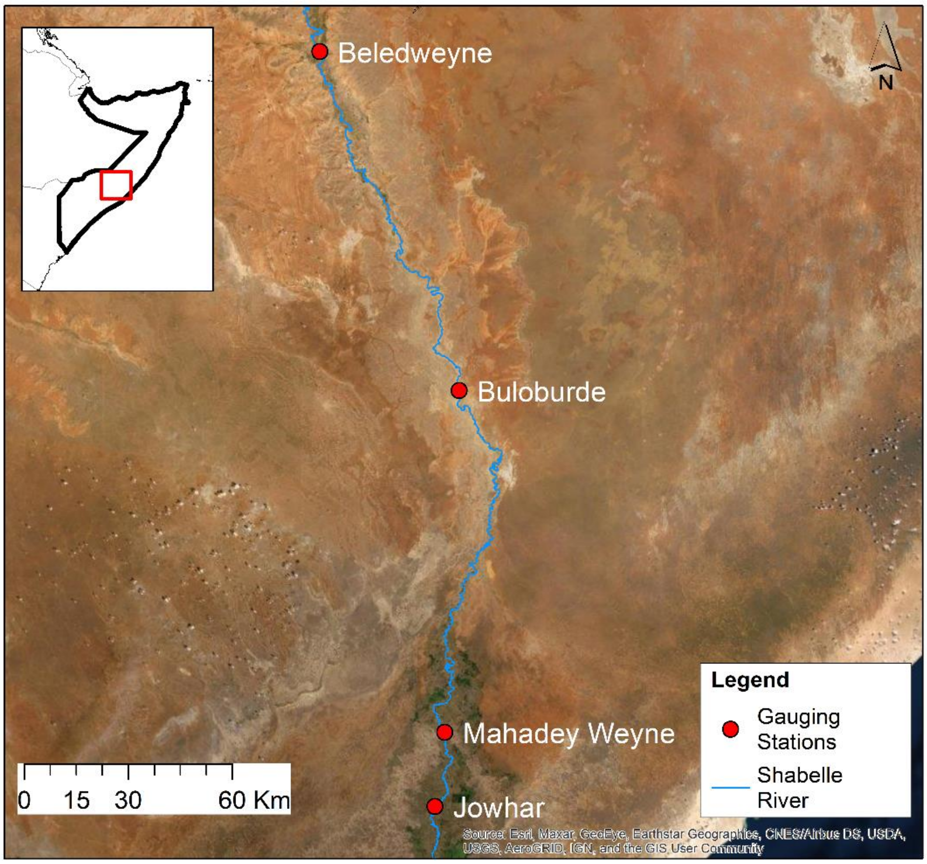


Figure 4.1 The investigated area of the Shabelle River in Somalia is from Beledweyne to Jowhar.

The primary objective of the sediment transport assessment is to inform prioritization of Nature-based Solution application for river embankment stabilisation and flood reduction. The following important components of the prioritisation have been identified:

- Develop understanding of system behaviour – which erosion and deposition processes are occurring in the river and where?
- Identify locations that are particularly vulnerable to bank collapse

- Construct a baseline sediment transport scenario that can be built upon to use in prioritisation
- Produce sediment transport scenarios to illustrate the effect of various interventions

Identification of vulnerable locations, of the processes causing bank collapse, and of the effectiveness of investigated interventions, will inform prioritization of where to intervene and selection of how to intervene during strategy development. Furthermore, the impact of data quality and availability on decision-making and on the data needs for sediment transport assessment has been addressed.

4.1 Sediment Transport Data

A variety of data sources have been used to inform the sediment transport assessment. Some have yielded general knowledge of the system and others have provided parameters or inputs to the sediment transport model. This section describes the collected, available data relevant for the sediment transport assessment of the Shabelle River system. The lack of available data as a limitation to the assessment is discussed in the Section Data limitations and during interpretation of the model results in Section 4.4 Nature-based Solutions.

4.1.1 Local evidence of siltation and flooding

News items posted by FAO-SWALIM and UN organizations over the past decade report flooding due to sediment phenomena in the Shabelle River. Some sources point to increased sediment deposition as the cause of flooding:

> “Factors other than the weather that has been playing a major role in causing the increased frequency of floods in the riverine areas is alterations in the natural environment for the past 27 years by increasing erosion rates which in turn results sedimentation in river channel making rivers shallower causing floods to occur even with low amounts of precipitation.” (FAO-SWALIM, 2018)

> “An estimated 10 centimetres of silt accumulates on the riverbeds seasonally, resulting in a loss of volume retained within the embankments” (OCHA, 2019)

And others point toward increased erosion of riverbanks as a main factor to increased flooding:

> “Factors such as weakened riverbanks as result of erosion along the river have also aggravated flooding events.” (FAO Regional Office for Africa, 2021)

Flooding can result from both erosion and deposition, but the methods to address each are not the same. A sediment transport model can help elucidate which processes are occurring and at which locations, to inform decision makers as they develop flood management strategies.

4.1.2 Information on vulnerable reaches / bank collapse

FAO-SWALIM tracks the status of river breakages in the Juba and Shabelle rivers. This data is available through the Flood Risk and Response Information Management System (FRRIMS) and through the FAO-SWALIM GeoPortal. This information is useful when evaluating the results of the sediment transport model. A snapshot of the data and description is shown in Figure 4.2.

Embankments are marked as:

Open: riverbank breakage that led to flooding within the past year that has not been addressed

Overflow: stretches of river where spillage has occurred with the past year and has not been addressed

Potential: at risk areas based on satellite image or field analysis.

Closed: Breakage point that has been addressed and where no flooding has been detected within the past two years.

Figure 4.2 FAO-SWALIM FRRIMS database for the target area, breakages from August 2021.

4.1.3 Riverbank cross sections

Cross sectional riverbank profiles were collected upstream and downstream of each of the Shabelle's gauging stations in 2018 (Somalia Water and Land Information Management, 2018). Approximately 6 cross sections were available at each of the locations surveyed. The river depths reported in the cross sections were matched to an elevation at each embankment from NASA's 30m SRTM DEM. This DEM was used because it is available for the entire modelled river reach (Farr et al., 2007).

The modelled length of the river is approximately 395 km. As there are only four surveyed locations along this stretch of river, there are many kilometres of river without cross-sectional information. Cross sections between sampling locations were interpolated at 10-20 km intervals using MIKE HYDRO River software.

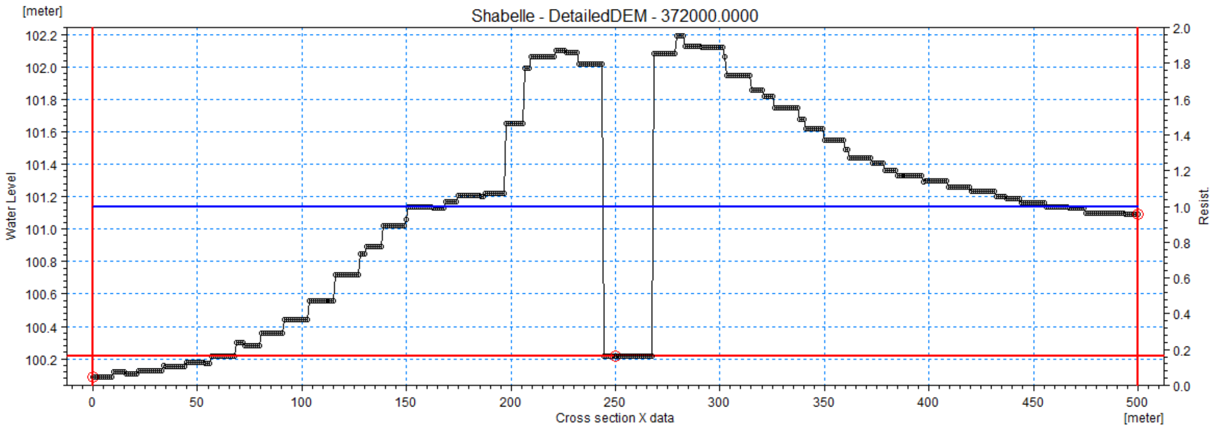


Figure 4.3 **Shabelle River cross section from the detailed DEM, where the river is high-lying relative to the surrounding floodplain.**

River cross sections interpolated using a detailed DEM, (Basnyat and Gadain, 2009), which is not available for the entirety of the river domain, give a good illustration of the river profile relative to the surrounding floodplain (Figure 4.3). In the downstream part of the modelled river reach, the area surrounding the river slopes upward to the embankments, and the Shabelle River itself is high-lying relative to the floodplain. This phenomenon is also observed in cross sections derived from aerial photographs in 2009 (Basnyat and Gadain, 2009).

4.1.4 Hydro-meteorological data

Water level time series for 2007-2008 were collected from the FAO-SWALIM river flow archive (FAO-SWALIM, 2021). Water level data are available in this time period for the Beledweyne, Buloburde, and Jowhar gauging stations.

Discharge data in this time period are available for the Beledweyne gauging station, however the rating curve used to develop these time series has not been updated since 1963 and is unlikely to reflect the state of the river today, nearly 80 years later. Using the measured cross sections and water level measurements in the hydraulic 1D model of the Shabelle (without sediment transport), bank full discharge at Beledweyne is estimated to be 200-300 m3/s. Similarly, bank full discharge for the Shabelle near the Duduble canal, located halfway between Mahadey Weyne and Jalalaqsi, is estimated at 100 m3/s. This is corroborated by the hydraulic analysis of the Shabelle from 2009 (Basnyat and Gadain, 2009). A discharge rating curve developed using HEC-RAS modelling was established in 2009, as an update to the 1963 rating curve (Basnyat and Gadain, 2009).

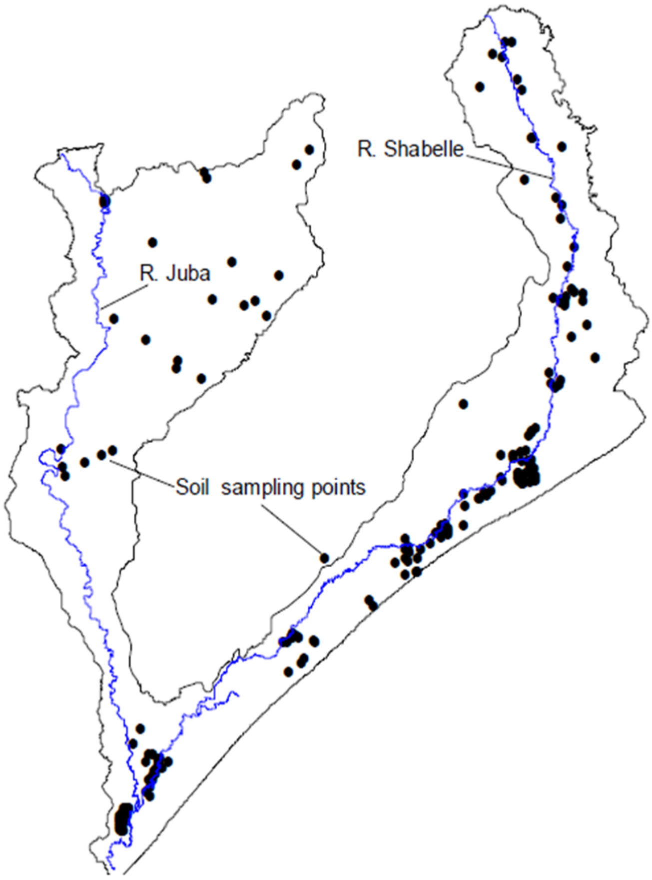
A hydrological model of the Shabelle River was developed to produce catchment runoff time series, to define the lateral inflows to the 1D sediment transport model. The hydrological model was developed in MIKE HYDRO Basin, which uses the NAM model. The precipitation dataset used in the model was the ERA5 rainfall product, at a daily temporal resolution and units of mm/d (ECMWF, 2021). The potential evaporation used was the MODIS PET product (see Section 3.3.2). Three catchments were modelled between Beledweyne and Jowhar, providing runoff time series for the length of the river reach investigated in this sediment transport assessment.

4.1.5 Grain size distribution

The diameter of a sediment grain is an important property in determining whether it will erode, deposit, or remain in suspension. This is because the grain diameter directly influences the fall velocity and hence affects the deposition rate, and because the incipient motion of a particle on the riverbed is partly a function of the grain diameter and hence influences the onset of erosion. Furthermore, the sediment transport rate is also a function of the grain size. Data describing the distribution of grain sizes of the river sediment is an essential component to sediment transport modelling. If a grain size distribution is lacking, grain sizes can be estimated from sediment size class datasets for clay, silt, and sand provided such are available.

No grain size distribution dataset for the Shabelle River was discovered during this assessment, and it appears that the most recent sediment size class dataset for Shabelle River sediment was produced in 1990 (Sir M MacDonald & Partners, 1991). The characteristics of the river have changed in the 30 years since this data was collected, and this dataset was not used in the analysis.

A grain size distribution estimate for the sediment in the Shabelle River was estimated based on the soil data reported in the 2009 FAO-SWALIM soil erosion study (FAO-SWALIM, 2009). It is assumed that sediment in the river is composed of soil eroded from the river basin, and that this is representative of the sediment size classes in lieu of measurement from the river. Grain sizes are proposed based on the sizes for medium clay, medium silt, and medium sand and are as follows: Clay, 0.0015 mm; Silt, 0.024 mm; and Sand, 0.375 mm (Julien, 1998).



Middle Shabelle

	Mean	Std. Deviation
Sand (%)	29.75	19.72
Silt (%)	31.91	11.85
Clay (%)	38.38	14.94
Sodium (Me/100g)	0.79	0.88
Carbon (%)	1.06	0.73

	Proposed grain size [mm]
Clay	0.0015
Silt	0.024
Sand	0.375

Figure 4.4 Soil sampling locations and soil data from soil erosion report L-16 (FAO-SWALIM 2009). Applied grain size based on soil classification (Julien, 1998).

4.1.6 Sediment rating curve

Sediment rating curves relate the sediment concentration or sediment load to the river discharge. Sediment rating curves are developed based on measured sediment concentration [g/m^3] vs discharge [m^3/s] and are used to develop sediment transport/concentration time series for known river discharges. A sediment rating curve was developed in the 2009 SWALIM soil erosion study based on data collected from the Juba and Shabelle rivers in 2007 and 2008 (FAO-SWALIM, 2009).

The relationship is $Q_{sediment} = 0.087 \times Q_{water}{}^{1.9645}$, which yields sediment discharge in kg/s based on river discharge in m^3/s The original data used to develop this rating curve was not available.

Sediment concentration time series at Beledweyne are developed for the model using this sediment rating curve and the discharge time series at Beledweyne (Hydro-meteorological data).

4.1.7 Soil erosion contribution to sediment load

Soil eroded by runoff over the land surface in the river basin also contributes to the total sediment load in the Shabelle River. The 2009 FAO-SWALIM soil erosion study estimated the topsoil loss in the Juba and Shabelle basins to be 21.46 ton/ha/yr (standard deviation of 4.7 ton/ha/yr) for 2007 and 15.48 ton/ha/yr (standard deviation of 9.11 ton/ha/yr) for 2008 (FAO-SWALIM, 2009). Based on these values for 2007 and 2008, 20 ton/ha/yr is applied during modelling. This number has been selected as a conservative estimate of the contribution from soil erosion and because the numbers are highly uncertain. The spatial distribution of the average topsoil loss values is depicted in the report (Figure 4.5).

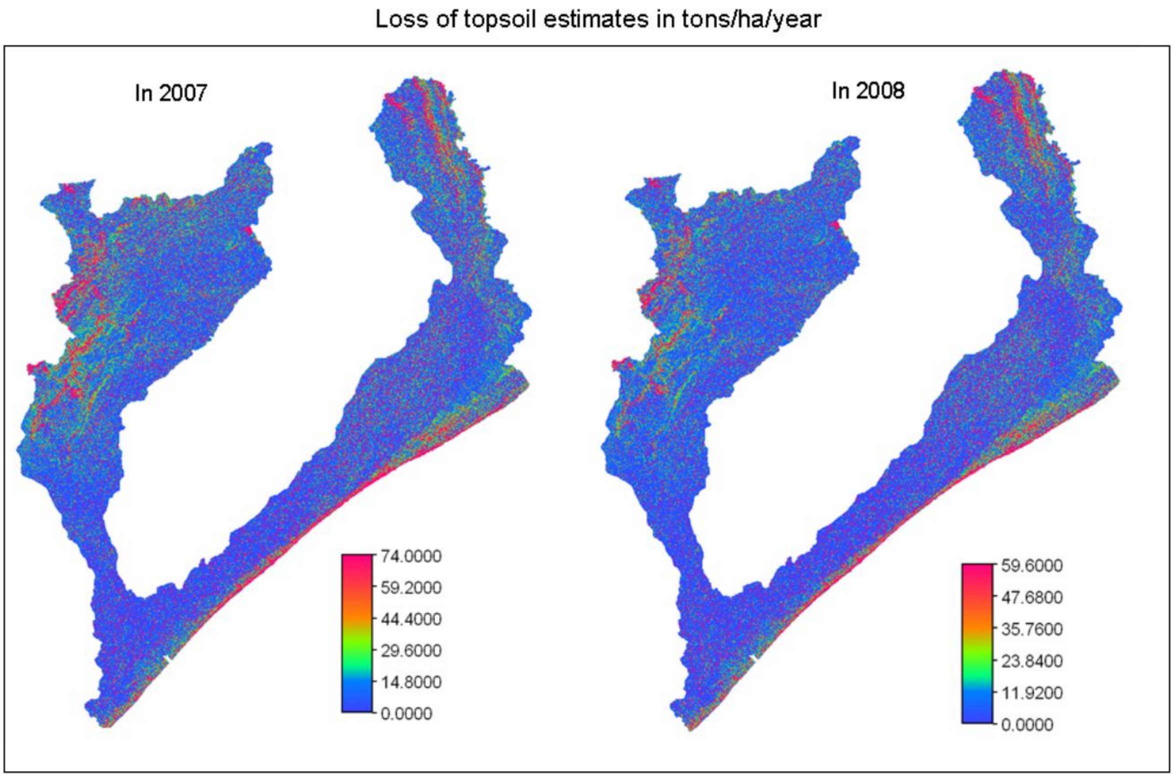


Figure 4.5 Topsoil loss estimates from 207 and 2008 computed using the MUSLE soil erosion model, as presented in the 2009 FAO-SWALIM soil erosion report (FAO-SWALIM, 2009).

4.1.8 Total suspended solids

Total suspended solids (TSS) measurements are measurements of sediment concentration in the river water column. In most reports used in the present study, a high value is considered > 45 mg/L.

The 2009 FAO-SWALIM soil erosion report states a value of 204 mg/L measured at Jowhar on April 18, 2008 (FAO-SWALIM, 2009).

The 2008 FAO-SWALIM river survey report presents TSS values at four locations in the modelled domain from a series of sampling campaigns from 2007 to 2008 (FAO-SWALIM, 2008). These are presented in Table 4.1. All reported values are much greater than 45 mg/L and are therefore considered high.

Table 4.1 TSS values in mg/L reported in the 2008 FAO-SWALIM river survey report for three sampling campaigns (Sep/Oct 07, Feb/Mar 08, and Mar/Apr 08) (FAO-SWALIM, 2008).

	Sep/Oct 07				Feb/Mar 08	Mar/Apr 08
Beledwyene				*04-10-2007* 1356		*03-04-2008* 664
Mahadey Weyne		*05-09-2007* 13896	*11-09-2007* 12400	*04-10-2007* 1356	*19-03-2008* 492	*01-04-2008* 616
Sabuun		*04-09-2007* 12852	*08-09-2007* 13372	*09-09-2007* 12480		
Jowhar	*04-09-2007* 12624	*10-09-2007* 10004	*12-09-2007* 11988	*13-09-2007* 10608	*19-03-2008* 564	*31-03-2008* 704

The TSS data available is relevant in that it gives an overall picture of the high sediment concentrations found in the Shabelle River. The TSS observations are far too few for model calibration and validation.

4.1.9 Infrastructure relevant to sediment transport

There are nine barrages located on the Shabelle River. The most upstream of the Shabelle barrages is likely to have the most impact on the sediment transported downstream from Ethiopia. This barrage, called the Sabuun barrage, is located upstream from the town of Jowhar and is the only barrage identified within the modelled river reach.

The Sabuun barrage is reported to be non-functional (MacDonald, 2015). When it was operating, it fed the FAO canal and a reservoir located 20km east from Jowhar (Gadain and Jama, 2009). The FAO canal and Jowhar reservoir are also reported to be silted over and no longer in use (FAO-SWALIM, 2010).

Images in an infrastructure Feasibility Report (MacDonald, 2015) from 2015 and Google earth images from March 2021 (Figure 4.6) show that, although the barrage may be non-functional, it is still present in the river. Such a structure in the river would impact how sediment is transported downstream. A barrage that is not maintained could increase sediment deposition and raise the riverbed level upstream of the barrage – indeed, it appears that an island is located just upstream of the barrage in Figure 4.6.

Figure 4.6 Sabuun barrage and FAO canal, located upstream of Jowhar town. Image from Google Earth, last updated March 2021. Right: Sabuun barrage, from upstream (MacDonald, 2015).

The feasibility report documents the dimensions of the Sabuun barrage: the structure is comprised of seven radial gates, each measuring 4m wide, and the gate sill is located 4.7m below the top of the structure (MacDonald, 2015). The report also notes that the barrage has been in a state of disrepair since prior to 1996. All seven of the barrage's radial gates have been removed, and water passes directly through the structure bays. Depth measurements were taken, and sediment was found to have accumulated by up to 2m above the gate sill on the upstream side of the barrage.

4.1.10 Sediment source analysis

The sources of sediment to the Shabelle River consist of upstream sediment transported within the river, local soil erosion from the part of the river catchment in Somalia, and a minor contribution from breakage of the embankments themselves. Each of these sources will be used to inform a boundary condition in the model (described in Section Sediment at boundaries). The relative contribution of these different sediment sources to the Shabelle River has been evaluated using the information known from the years 2007 and 2008, when much of the data used to inform the knowledge on sediment was collected and applied to the baseline year 2020.

By using the sediment rating curve presented in Section Sediment rating curve, the annual amount of sediment transported from upstream at Beledweyne was calculated for the years 2007 and 2008. The average sediment load for the two years amounts to approximately 35 million tons.

The average annual soil erosion rates from 2007 and 2008 amounts to 18.5 ton/ha/year. Not all eroded soil enters the river due to natural depressions in the landscape. Furthermore, the calculated soil erosion potential does not account for the transport capacity of the overland flow that erodes the soil. Based on experience from similar studies, it is not uncommon to apply a reduction factor of 2-3 to soil erosion rates (DHI A/S, 2020). In addition, not all tributaries/wadis to the Shabelle are directly connected to the river, as elevated embankments impede sediment transport from land to the river. By inspecting recent satellite images of the river, a rough estimation is that a reduction factor of approximately 5 would be realistic to account for this effect. In total, including a sediment loss factor of 10, the sediment load from locally eroded soils amounts to approximately 1.2 ton/year.

Because embankments are weakened due to overtopping of flood water, they often breach and the bank material is dislodged and slides into the river profile. A similar effect can happen in the case of manmade breakages. An estimation of this amount can be made by assuming a breach depth and width of embankments on either side of the river and combining this with the total length of the breaches. For 2020, the total length of breaching (FAO-SWALIM GeoPortal) amounted to approximately 22km. Assuming a width of 2 m and a depth of 1.5 m of the breaches results in a total amount of 132,000 m^3 or 349,800 tons of sediment added to the river due to embankment breakages. These assumptions are judged to be on the conservative side.

The magnitude of the contribution from each of the three different sources described above is shown in Figure 4.7. The soil erosion contribution accounts for 3.5% of the total load in the river at Beledweyne. The embankment breach accounts for 1.0 % of the total load at Beledweyne. The rest, 95.5%, is transported from upstream by the river at Beledweyne.

The most effective ways to intervene using Nature-based Solutions to alter sediment dynamics and reduce river flooding are not able to be determined solely from an analysis of the magnitude of the sediment sources. A sediment transport model is necessary to understand how each source impacts sediment behaviour in the Shabelle River.

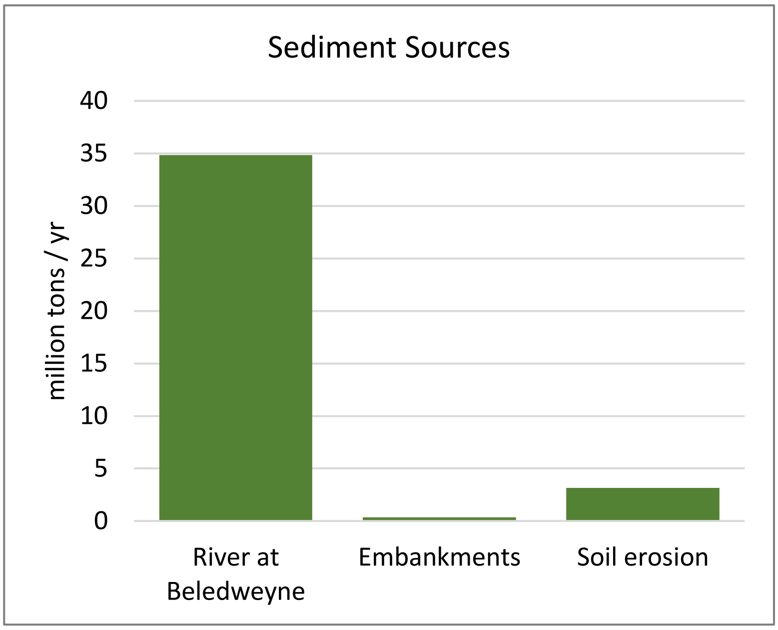


Figure 4.7 Contribution from sources of sediment to the Shabelle River in Somalia.

4.1.11 Data limitations

The data presented in this report do not by themselves lead to any conclusions regarding the causes for increased flooding along the Shabelle River and how this is related to the sediment processes. For this a mathematical model is required.

To assess sediment transport in a river by modelling, it is necessary to know various details of the state of the river. The physical characteristics of the river, from river cross-sections and DEM information along with the flow characteristics and runoff, are used to describe the river hydraulics. In addition, any large infrastructure impacting the flow must also be included in the model setup.

As for sediment specific data, one of the most essential data types is the grain size distribution of suspended sediments and of riverbed material, as this has a significant impact on the modeled sediment behavior. Known sediment concentrations, from time series TSS measurements and/or sediment rating curves are also essential to the model setup.

Many of these data types were many years old, sparsely collected, or unavailable. Steps were taken during data processing, such that the data was suitable for model setup. For example, cross sections were interpolated between measured locations and grain size distributions of topsoil in the basin are used lieu of measured data for particles in the river.

The conclusions made using the sediment transport model can only be as strong as in the validity of the data used to setup and feed this model; model conclusions will reflect the input data limitations.

4.2 Modelling Approach and Setup

The data described in Section 4.1 Sediment Transport was used to produce a 1D sediment transport model for the Shabelle River from Beledweyne to Jowhar. The following section describes how the collected data was used to setup the model and estimate important model parameters.

4.2.1 Modelling Approach

The first step to using a model to assess the impact of various interventions on sediment transport, embankment collapse, and flooding in the Shabelle River is to create a baseline simulation. This includes the hydraulic river model and a sediment component, without any interventions applied. The baseline simulation serves as the best estimate of the state of the river, and interpretation of the baseline simulation results is useful to understand the Shabelle's underlying behaviour and characteristics.

Scenarios to test the effect of Nature-based Solutions can then be modelled, and their results compared to that of the baseline simulation. Changes were made to the sediment boundaries in the baseline model setup to test Nature-based Solutions in three groups:

- Bank protection and stabilisation efforts along the Shabelle in Somalia
- Reforestation / re-vegetation, implementation of sand dams, and gully protection of the Shabelle catchment in Somalia
- Reforestation / re-vegetation of the Shabelle catchment in Ethiopia

Modification of the sediment boundaries and to test application of the Nature-based Solutions is described further in Section 4.4 Nature-based Solutions.

As mentioned in Section Data limitations, creation of the baseline simulation is complicated by lack of available data. Because input data is sparse and coarse, only coarse conclusions can be drawn from the model outputs.

4.2.2 Hydraulic Model Setup

A one-dimensional hydraulic model of the Shabelle river was constructed using the MIKE HYDRO River software. This hydraulic model provides the basis for sediment modelling and also yields insights as to river spillage along the length of the modelled river reach. It is the first step in creation of the baseline model.

The model domain extends from the river gauging station at Beledweyne to the river gauging station at Jowhar. As the sediment assessment is only conducted within the banks of the river and not on the floodplains surrounding the river, the model domain is constricted to within the riverbanks.

The hydraulic model physical characteristics are derived from cross section data (Somalia Water and Land Information Management, 2018) and a DEM (Farr et al., 2007) (See Section Riverbank cross sections). Cross sections were interpolated at 10-20 km intervals between the observed cross sections at Beledweyne, Buloburde, Mahadey Weyne, and Jowhar. A longitudinal profile of the Shabelle River from Beledwyene to Jowhar is shown below.

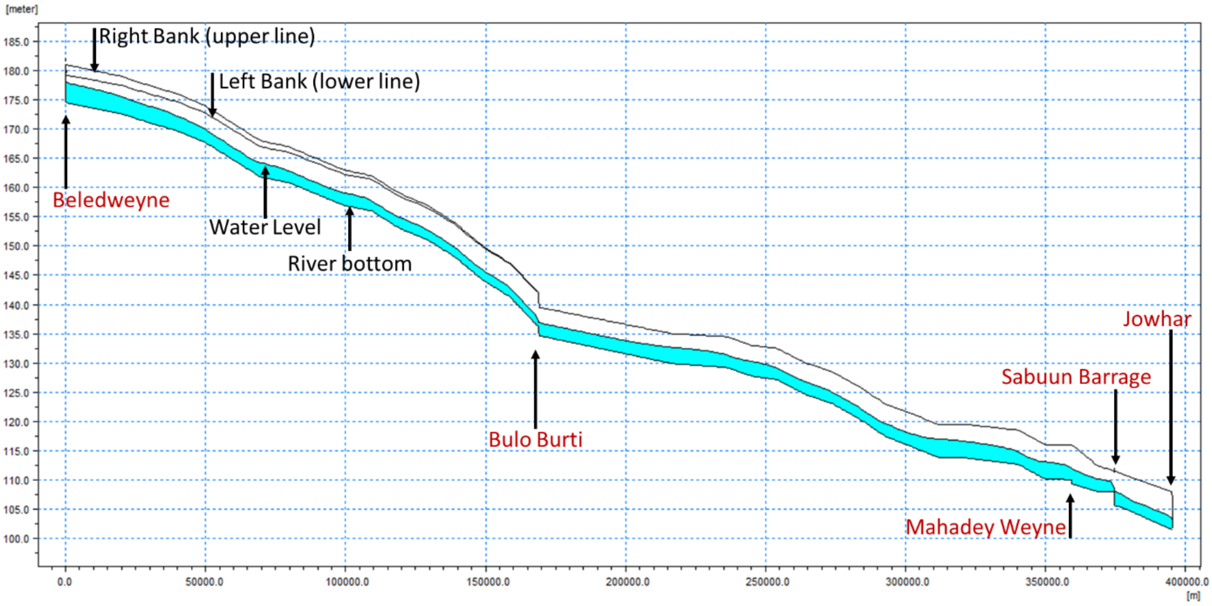


Figure 4.8 Longitudinal profile of the Shabelle River hydraulic model. Plot components are indicated in black text. Locations of towns and structures are indicated in red text

Inflows to the river were defined as a) flow upstream from Beledweyne and b) lateral inflow as run-off from catchments.

During development of the hydraulic model, an updated discharge time series was also developed to yield a reasonable number of days of spilling when the 2018 measured cross-sections were used to define the river geometry. The rating curve relating the discharge and water level was $Q = 169 \times h^{0.0127}$, where Q (m^3/s) is discharge and h (m) is water level. It was developed based on the river physics using the MIKE HYDRO River hydraulic model. Because the hydraulic model is in-bank only and does not include the floodplains, water spilled to the floodplains during flooding must be removed from the system. This was accomplished by modifying the discharge model input time series during times of spilling at Beledweyne to not exceed bank full discharge.

Run-off inflow is added as a distributed boundary along the length of the river, rather than as point sources from tributaries. Three catchments were defined in the hydrological model along the hydraulic model domain – one from Beledweyne to Buloburde, one from Buloburde to Mahadey Weyne, and a last from Mahadey Weyne to south of Jowhar. The run-off modelled for these three catchments was used as boundary conditions in the hydraulic model. It was estimated that one third of the run-off from the most downstream catchment enters the river upstream of Jowhar. A discharge-water level relationship is applied to the downstream boundary at Jowhar. In lieu of known initial conditions, a steady-state initial condition is applied.

The model was roughly calibrated using water level data (FAO-SWALIM) for the year 2008, as sediment data was also available for this year. In the absence of hydraulic data for model calibration the bed resistance or roughness coefficient (Mannings M) needs to be estimated rather than calibrated. Estimation principles exist in which the channel material, irregularity and variations of the cross sections, the presence of obstructions, vegetation state and the degree of meandering is considered. The method described in (Chow, 1959) has been applied in the present study. By making best estimates of the mentioned parameters, a Manning's M value of 35 $m^{0.33}/s$ results. This value represents a smooth as opposed to a rough river channel, and values of this magnitude has been used by DHI in other similar river systems. This bed resistance coefficient value is applied throughout the river system and at all time periods.

4.2.3 Structures affecting sediment transport

The Sabuun barrage, located between Mahadey Weyne and Jowhar, was identified as likely to impact sediment transport and warrants inclusion in the model. The barrage was implemented by creating a cross section at the barrage location with the dimensions of the barrage to allow for the constriction effect of the barrage. Because it is known that significant sedimentation has accumulated upstream of the barrage (MacDonald, 2015), the interpolated cross sections upstream of the barrage were modified to include a maximum depth equal to the amount of sedimentation known to have occurred at the barrage.

The sediment transport assessment conducted in this study is in-channel only for the Shabelle River and does not include sediment transport processes in gullies or irrigation canals. Reports of irrigation infrastructure do indicate significant siltation in irrigation canals, in some cases these canals are now filled with sediment. This fits with reports that the clay and silt content of the river water in the Shabelle is high, as these grain sizes pass through the system and do not significantly impact the morphology of the river itself but may cause problems when flow velocity slows down in irrigation areas. At a lower flow velocity, the fine particles may deposit. This can decrease volume in irrigation channels, deposit onto crops, and in general make uncontrolled and unfavourable changes to the landscape. It may also have the benefit of bringing nutrients to fields, which may be favourable for crop production. In some areas in the main channel, such as upstream of the Sabuun barrage, deposition does impact the river morphology, and this may impact adjacent irrigation channels as the flow may be difficult to control.

4.2.4 Sediment at boundaries

Sediment transport was then added to the hydraulic model. Sediment inflows were described from a) load in the river from upstream of Beledweyne, b) load in the run-off, from distributed, lateral contributions to the river and c) load added via bank collapse (these three sources depicted previously in Figure 4.7).

Sediment load in the river from upstream of Beledweyne was calculated using the sediment rating curve determined in the FAO-SWALIM L-16 soil erosion study (FAO-SWALIM, 2009). The sediment rating curve relates the sediment concentration to the known river discharge. The relationship determined for the Juba and Shabelle rivers in 2007 and 2008 was $Q_{sediment} = 0.087 \times Q_{water}{}^{1.9645}$, which yields sediment discharge in kg/s based on river discharge in m^3/s. The sediment load of the water modelled as lost to the flood plains was also modelled to leave the in-bank system.

Lateral sediment contributions to the river were determined based on the amount of topsoil calculated to erode from the three catchments contributing to the river with run-off. Models in the soil erosion study established 21.46 ton/ha/yr and 15.48 ton/ha/yr of topsoil loss for 2007 and 2008, respectively. A figure of 20 ton/ha/yr of topsoil loss was used for both modelled sediment transport years, 2008 and 2020. To account for deposition of lost topsoil in depressions on land and for the Shabelle embankments acting as a barrier to entry, a loss factor of 10 was applied, see explanation in section 4.1.10. A time series of sediment contributions by erosion was calculated using the area of each of the three contributing catchments and by scaling the addition throughout the year assuming a constant sediment concentration (ton sediment per m^3 run-off).

Sediment added to the river via bank collapse was estimated based on the embankment breach data in the FAO-SWALIM GeoPortal. The total length of breaches for 2020 (approximately 22 kilometres) was converted to a mass based on an estimated 1.5m depth, 2m width, and 2.65 ton/m^3 density of the eroding embankment. The resulting approximate mass of sediment per year, 200,000 tons/yr, was converted to a daily time series by scaling the magnitude of the daily added sediment to the magnitude of the river discharge.

4.2.5 Sediment fractions

Grain size is one of the most important parameters in sediment transport modelling, as the size of a sediment particle determines its behaviour at a given flow velocity and sediment concentration. The grain size distribution of the Shabelle River sediment is unknown, and this gives great uncertainty as to sediment dynamics in the model. The grain sizes have been estimated from characterisation of the Shabelle basin topsoil as sand, silt, and clay (FAO-SWALIM, 2009). Based on experience with other systems, the total sediment mass was distributed into six fractions – one clay, two silt, and three sand fractions – based on the topsoil characteristics for the Middle Shabelle basin of 29.75% sand, 31.91% silt, and 38.38% clay. Due to lack of detailed information, the mass of sand was evenly divided between the three sand fractions, and the mass of silt was evenly divided between the two silt fractions. The properties of each fraction are listed in Table 4.2. Non-cohesive fractions were modelled using the van Rijn transport model. Cohesive sediment fractions were modelled using an advection-dispersion transport description with riverbed exchange in terms for erosion and deposition. The important parameters for the cohesive model are the critical shear stress thresholds for erosion and deposition. These thresholds have been defined on basis of experience and engineering judgment.

Table 4.2 Sediment fraction properties.

Fraction	Sediment Type	Grain Size [mm]	Erosion Shear Stress Limit [N/m^2]	Deposition Shear Stress Limit [N/m^2]
Medium Clay	Cohesive	0.0015	0.1	0.07
Medium Silt	Cohesive	0.0235	0.3	0.2
Coarse Silt	Cohesive	0.0465	0.6	0.5
Fine Sand	Non-Cohesive	0.1875	--	--
Medium Sand	Non-Cohesive	0.375	--	--
Coarse Sand	Non-Cohesive	0.75	--	--

For the grain size distribution of the sediment at the upstream boundary at Beledweyne, the sand fraction was reduced by 95%. This was chosen to mimic the tendency of sand to deposit in the upper reaches in the Shabelle river, such that most of the incoming mass of sediment carried by the river is silts and clay. At this boundary, the distribution was 3% sand (1% for each sand fraction), 44% silt (22% for each fraction) and 53% clay. Because the sand fraction in this source was lowered, the mass at this boundary was also lowered accordingly.

4.2.6 Initial sediment concentration

Concrete data regarding the sediment conditions of the river are in general unknown, and therefore there is no known state that could be used as an initial condition for the model. Because the initial riverbed morphology is unknown, an initial warm-up period is applied when running model simulations. The initial sediment concentration in the river, at the beginning of the warm-up period, is zero. The baseline year, 2020, is then repeated five times consecutively (from 2015-2020), such that the river morphology and initial suspended sediment concentration could reach a reasonable initial state before results would be used for interpretation.

4.2.7 Riverbed sediment composition

Information regarding the Shabelle riverbed is lacking. Based on prior experience in other systems, there was no limitation applied to the sediment availability of the riverbed. The initial bed composition was estimated to be 25% Medium Clay, 30% Medium Silt, 30% Coarse Silt, 5% Fine Sand, 5% Medium Sand, and 5% Coarse Sand. Sand fractions comprise only 15% of the initial bed composition, as it is considered that finer particles, clay and silt, are the principal components of the river system.

The sediment availability at the Sabuun barrage was set to zero, to account for the structure. The concrete sill of the barrage cannot be eroded.

4.3 Baseline

The model setup described above was used to produce a baseline simulation for the year 2020. The baseline simulation serves as a best estimate of the behaviour of the Shabelle River during this year. The baseline results not only yield an understanding of the Shabelle River, they also serve as a control against which the impact of Nature-based Solution implementation can be compared.

The baseline scenario simulated concentrations fit with the measured TSS values presented in Section 4.1.8. Maximum values of around 10,000 mg/L were simulated in September and October during the Deyr rainy season, and minimum values of around 100 mg/L were simulated in February and March. The simulated and observed values are on the same order of magnitude; because so few TSS measurements are available, a calibration was not possible.

Analysis of the contribution of sediment dynamics to flooding in the Shabelle River has two components: 1) determination of the dominant process (deposition or erosion) occurring in the river and 2) determination of the dominant process at known overflow locations. The trends in the river are ascertained by the sediment balance and changes in bed level in the model results.

4.3.1 Sediment balance

The law of conservation of mass applies to sediment dynamics in the river. If less sediment leaves the modelled river reach than enters, then there is a net deposition of sediment in the modelled system. Conversely, if more sediment leaves the modelled river reach than enters it, there is net erosion.

The total mass of sediment entering the system is the sum of the three boundaries: the upstream boundary at Beledweyne, representing the sediment carried by the river crossing the border from Ethiopia; lateral contributions from the Somali catchment carried by runoff; and sediment added to the river by riverbank collapse. The total mass of the sediment leaving the system is the sediment that crosses the downstream boundary at Jowhar.

For the baseline scenario for 2020, 28.0 million tons were simulated to enter the river over the course of the year (Figure 4.9). This is lower than the estimate in preliminary source estimation calculation (Figure 4.7), because the sand fraction of the incoming sediment from Ethiopia was reduced. The reduction was applied based on preliminary sediment simulations showing that sand is most likely to deposit in the system and is not likely to be carried by the river – it is likely that sand entering the system from the Ethiopian Shabelle catchment will deposit before entering the model domain starting at Beledweyne.

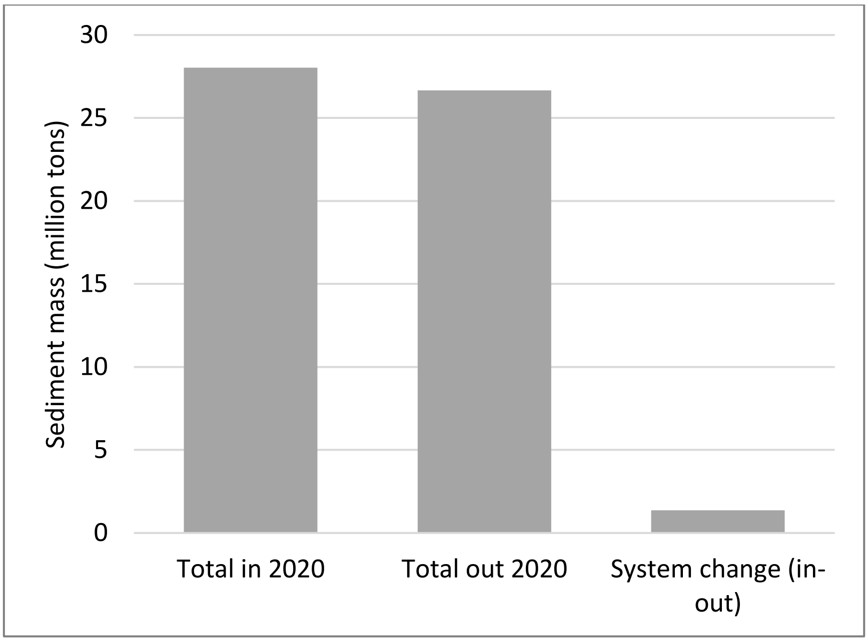


Figure 4.9 Sediment mass balance for the 2020 baseline scenario.

The total sediment that exits the system at Jowhar in the baseline scenario is 26.7 million tons; 1.4 million tons remain as deposited sediment in the system. The sediment mass balance analysis indicates that the baseline scenario exhibits deposition as a dominant sediment transport process.

4.3.2 Change in bed level

The change in riverbed level through time indicates the dominant process occurring at that computation point. Most locations on the river undergo both erosion and deposition – the bed level rises and falls in elevation throughout the year. However, there can be a net tendency to erosion or deposition when the change in bed level is observed over many years. The baseline simulation setup for 2020 was run starting from 2015, with 2015 acting as a warmup year (see Section Initial sediment concentration) and the last four years (shown as 2016-2020 on the x-axis in Figure 4.10) were used for the bed level analysis.

The bed level elevation of three locations at the upstream, midway, and downstream sections of the Shabelle River modelled domain are shown in Figure 4.10. Consistent deposition is exhibited at Beledweyne, as the bed level only increases in elevation. Buloburde and Jowhar exhibit deposition and erosion, as the bed level both increases and decreases through time, with a net tendency toward deposition.

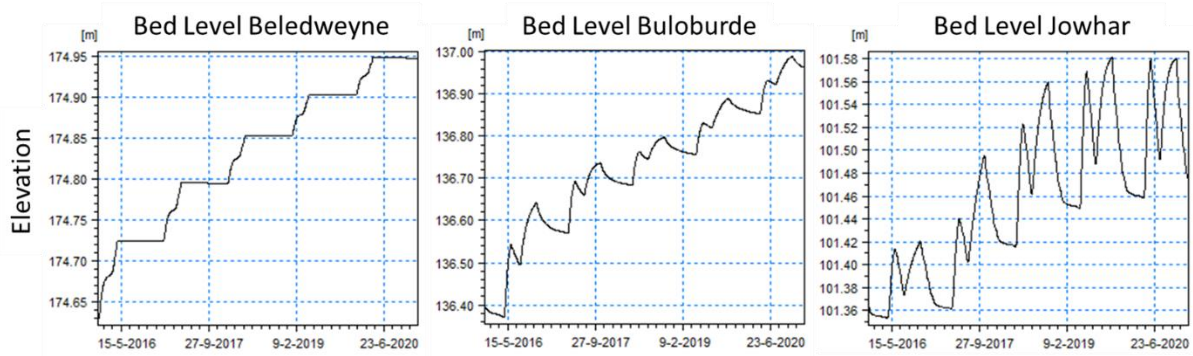


Figure 4.10 Bed level elevation changes at three locations along the river profile: Beledweyne (upstream boundary), Buloburde (midway), and Jowhar (downstream boundary). X-axis in each of the three panels is time, from 01-01-2016 – 31-12-2020.

The net change in bed level through time visualized along the length of the river profile illustrates the tendency in each computational point (each 10-20km) to deposit or erode (Figure 4.11). Values in Figure 4.11 that are above zero show that the bed level has increased in elevation of the five-year simulation, from 2015 to 2020, which indicates net deposition at these locations. Values below zero show the bed level elevation has decreased, which indicates net erosion.

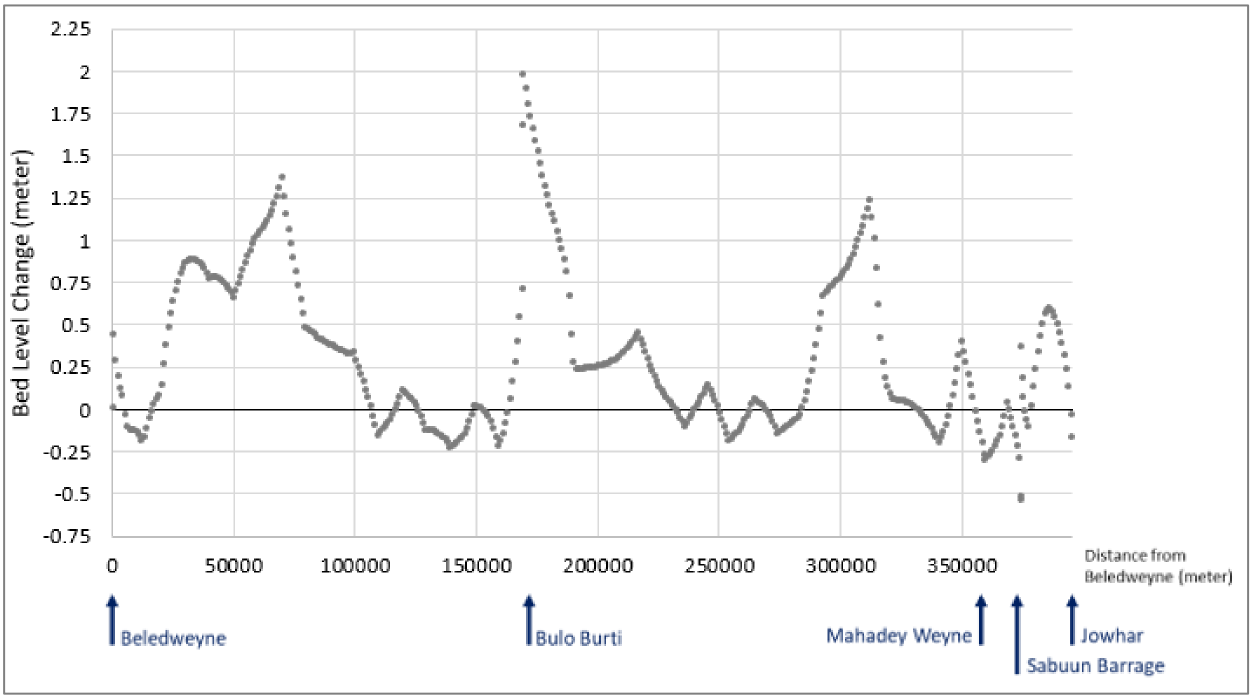


Figure 4.11 Change in bed level elevation in the baseline scenario over five years of simulation

4.3.3 Identification of depositing and eroding river reaches

The change in bed level elevation over the length of the river profile from beginning to the end of the simulation period gives an indication that the dominant process in the river is deposition (Figure 4.11; Section 4.3.2). However, to know for certain which process is dominant at each computational point, a time point with the same hydrological condition must be compared between two years.

When the river discharge is increasing with the onset of a rainy season, there is the most erosion possible in the river, as the flow velocity is high. Comparing the bed level elevation for these two situations for the simulated year 2019 and 2020 will show which locations are depositing and which are eroding. The results are displayed in plan view in Figure 4.12.

Deposition is the predominant process from km 0-11, 17-131, 157-237, 254-273, 286-339, 349-359, and 375-395. Erosion is the predominant process from km 11-17, 131-157, 237-254, 273-286, 339-349, and 359-375. Of the 395km of river modelled, 91km exhibit erosion as a primary sediment transport process and 304km exhibit deposition. This corresponds to 23% and 77% of the modelled domain as eroding and depositing, respectively.

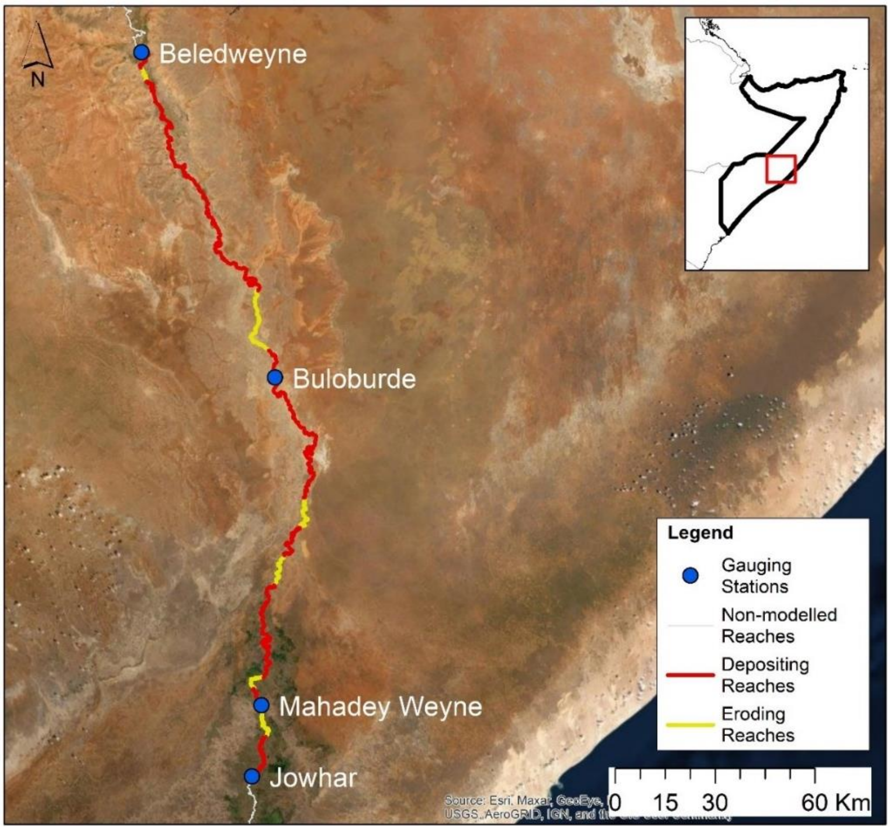


Figure 4.12 Depositing and eroding river reaches in the Shabelle river as identified from the baseline scenario.

4.3.4 Identification of sediment processes in overflow locations

The establishment of deposition as the primary sediment transport process occurring along the length of the modelled river domain is not sufficient to determine the process that most impacts flooding. To determine which process acts to destabilize the riverbanks, the overflow sites recorded by FAO-SWALIM from the baseline (FAO-SWALIM FRRIMS database) year can be aligned with the known depositing and eroding reaches. Figure 4.13 shows the location of the depositing and eroding river reaches in profile view (shown in plan view in Figure 4.12).

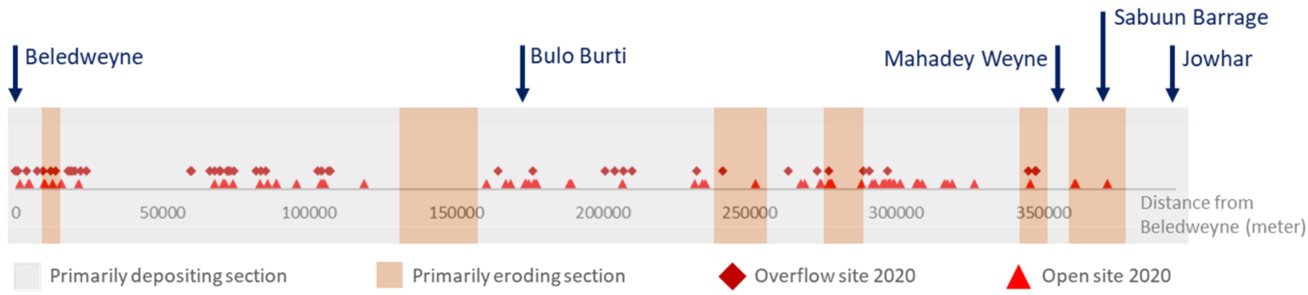


Figure 4.13 Location of eroding and depositing river reaches shown in profile (grey and brown coloured panels). Location of overflow and open sites from the FAO-SWALIM FRRIMS database for baseline year, 2020.

From this overlay of the two datasets, it can be seen that while not all overflow sites are in depositing river reaches, most are. 17% of the overflow sites by number and 17% of the overflow sites by length are located in eroding reaches; 83% of the overflow sites by number and length are located in depositing reaches. Since 23% of the length of the modelled section of the river is eroding and 77% depositing, and the location of the breakages are distributed approximately with the same ratio, it does not appear that erosion is an important process contributing to riverbank destabilisation and collapse. Figure 4.14 displays in numbers what Figure 4.13 displays visually.

Overflow Deposition *40 sites* *17678 meters*	**Overflow** Erosion *8 sites* *3558 meters*
Open Deposition *64 sites* *739 meters*	**Open** Erosion *14 sites* *113 meters*

Figure 4.14 Location of overflow and open sites from the FAO-SWALIM FRRIMS database for the baseline scenario year 2020. The grey boxes represent sites found in depositing reaches; the brown boxes represent sites found in eroding reaches.

4.3.5 Baseline Shabelle River behaviour

The sediment mass balance shows that net deposition occurs over the baseline simulation year. Bed level change analysis through time and over the length of the modelled domain corroborate the mass balance results and also indicate that deposition is the dominant sediment transport process.

A comparison of the bed level between two days with the same hydraulic conditions in the simulation years 2019 and 2020 reveals which river reaches primarily experience erosion and deposition. While most locations along the river experience both erosion and deposition, 23% of the river is primarily eroding, and 77% is primarily depositing. The overflow riverbank breakages are proportionately distributed between eroding and depositing river reaches, indicating that erosion is not an important process for riverbank collapse.

Due to the coarseness of the DEM and the few cross-section measurements available, more detail in the processes identified in the river reaches cannot be obtained. The maximum resolution possible is 10-20km stretches of river. Due to the lack of knowledge as the characteristics of the sediment, in particular grain size is unknown, the analysis above, Nature-based Solutions should focus on reducing the amount of sediment that enters the river, to decrease deposition and reduce the incidence of sediment-related flooding.

4.4 Nature-based Solutions Investigated

Nature-based Solutions that can reduce the sediment load entering a river and thus reduce the incidence of sediment-related flooding are detailed in the Nature-based Solutions Catalogue (see description in section 2). In this section, a selected array of Nature-based Solutions is investigated based on their method of action to reduce sediment load in the river. Three methods are investigated by comparison of the simulated Nature-based Solution application scenario results to the baseline simulation results.

The three methods of action investigated, hereafter referred to as the three scenarios, each impact one of the three sediment sources identified in Section Sediment source analysis. The three sediment sources, the method of action that can reduce sediment and impact flooding, and selected Nature-based Solutions that can bring about this action are listed in Table 4.3.

Table 4.3 Methods of action of Nature-based Solutions to reduce sediment from the sediment sources included in the sediment transport model.

Sediment Source	Sediment Reduction Method	Selected Nature-based Solutions
Embankment collapse	Prevent collapsed bank sediments from entering river	- Vegetated gabions - Bank revegetation
Soil erosion in Somali Shabelle catchment	Prevent eroded topsoil from Somali catchment from entering river	- Gully rehabilitation - Sand dams - Revegetation in Somalia
Load in river at Beledweyne	Prevent eroded topsoil from Ethiopian catchment from entering river	- Revegetation in Ethiopia

It is important to note that multiple Nature-based Solutions can have the same impact on the sediment in the river, although they might work on different time scales to have full effect. For example, revegetation / reforestation in the catchment prevent topsoil from entering the river by preventing erosion from occurring in the catchment, while sand dams trap eroded topsoil to prevent it from entering the river. The sediment transport model is an in-channel model only, and the catchment area and gullies where the sand dams would be placed are not explicitly included in the model. Thus, both of these Nature-based Solutions are implemented in the model by modifying the boundary condition for eroded topsoil entering the river. From the perspective of the river channel, the application of both Nature-based Solutions produces the same sediment reduction effect, and differences come only with the effectiveness of the application (i.e. the magnitude of the sediment reduction).

To analyse the results of each scenario, the sediment mass balance and bed level elevation changes are compared to the baseline. Because the scenarios have the end goal to reduce flood risk, it is not sufficient to only determine the impact of the Nature-based Solutions on sediment, as the impact of the sediment reduction on flooding must also be ascertained. To do this, the incidence of flooding at Buloburde is used as a gauge. The changes in sediment dynamics from the scenarios tested on the upstream half of the river are captured in the analysis at this measurement station. In the baseline scenario, overbank spilling occurs for 21 days at Buloburde.

4.4.1 Bank Stabilisation

The first Nature-based Solution scenario tested is that for bank stabilisation as a flood management intervention. The objective of this scenario is to ascertain the impact of reducing the amount of sediment that enters the river due to bank collapse on river flooding. Because the resolution of the model is relatively coarse (computational points every 10-20km), local effects of bank collapse cannot be obtained from the model. The model can only show the effect of bank collapse on river flooding at a larger scale.

The Nature-based Solutions selected that can reduce the sediment load added to the river due to bank collapse are those that stabilise the banks, such as vegetated gabions and bank vegetation. The tested scenario with application of these Nature-based Solutions assumes perfect, ideal application, where all 395km of both the left and right riverbanks are protected, and no sediment from bank collapse enters the river during the simulation. This is an extreme scenario that would be impossible to execute in reality; however, it is also an enormously valuable modelling exercise, because much can be learned about how Nature-based Solutions for bank stabilisation impact flooding. The scenario is referred to as “Maximum Bank Protection” and is implemented by setting the bank sediment boundary to zero for the entirety of the five-year simulation period (including the warm-up period). The other two sediment boundary conditions – the upstream boundary at Beledweyne and the lateral boundary for topsoil erosion – remain the same as in the baseline.

The sediment mass balance for the bank stabilisation scenario and the baseline scenario are displayed in Figure 4.15. The total sediment that leaves the system is the same in both scenarios, 26.7 million tons. The total sediment that enters the system and that remains in the system as deposited sediment is 0.4 million tons less in the Maximum Bank Protection Scenario compared to the baseline. 1.4 million tons remains deposited in the system during the baseline simulation, and 1.0 tons remains deposited in the system during the scenario.

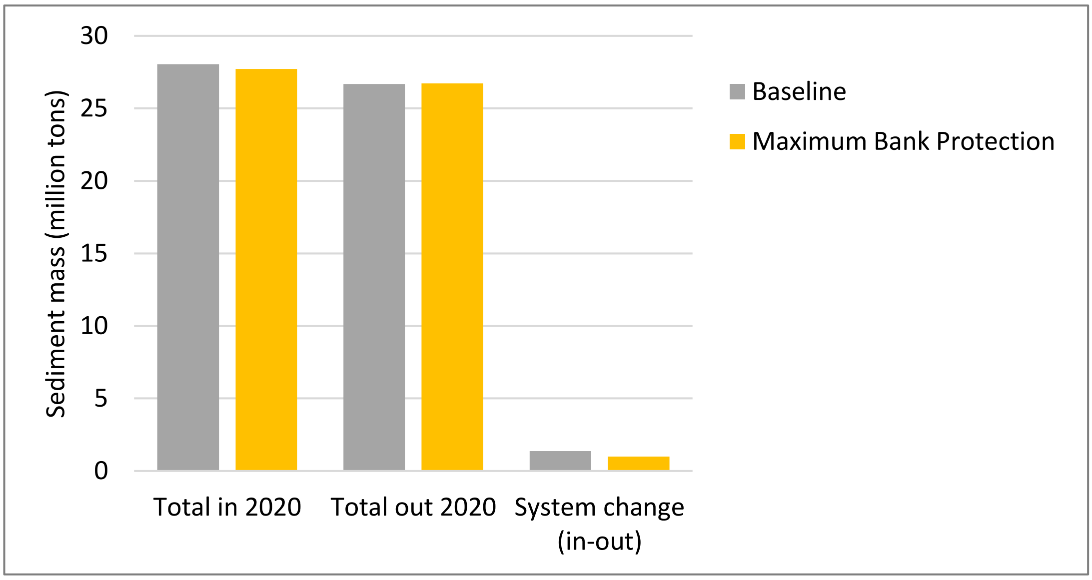


Figure 4.15 Sediment mass balance for the baseline simulation and bank stabilisation Nature-based Solutions scenario “Maximum Bank Protection” for year 2020.

The difference in bed level between the baseline and Maximum Bank Protection scenario also show that less deposition is occurring with intervention applied (Figure 4.16). The bed level is on average 2.5-3.0 cm lower in the scenario than in the baseline, indicating that this is the amount of deposition prevented by application of the intervention for the five-year simulation period.

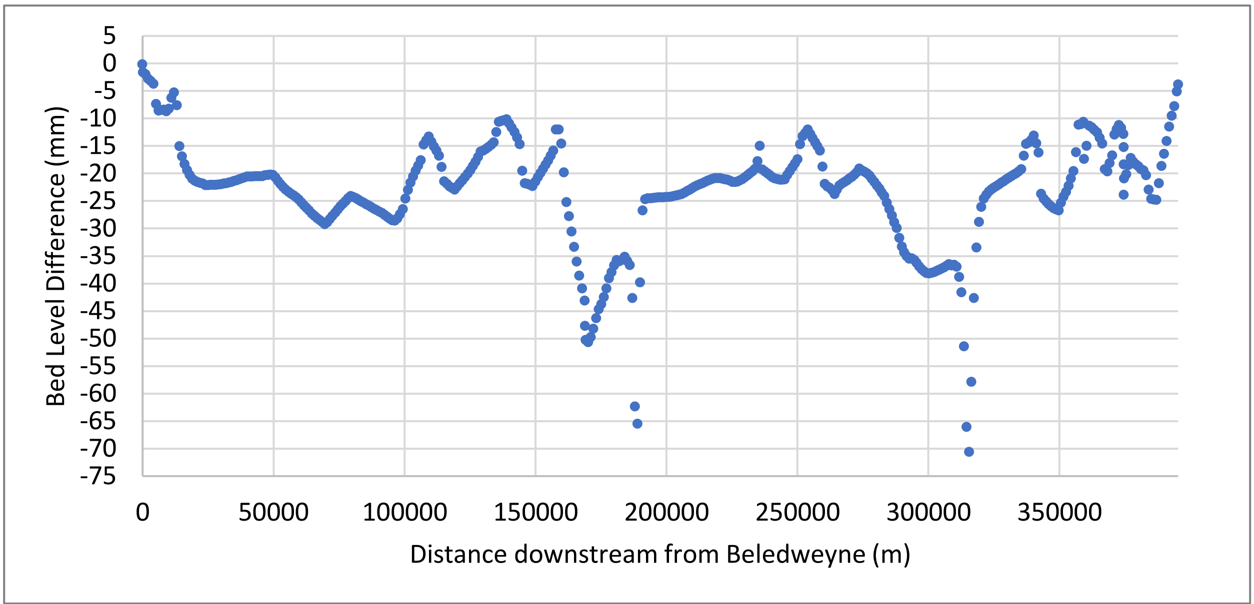


Figure 4.16 Difference in bed level elevation at the end of the simulation period for each computational point between the baseline scenario and the Maximum Bank Protection Scenario.

The plot shows the Scenario minus Baseline. Negative values indicate that the bed elevation in the scenario is lower than the bed level in the baseline. Note the unit of the Y-axis is millimetre.

While the results show that there is sediment deposition reduction caused by application of the intervention, a larger change would need to be shown by the Maximum Bank Protection scenario to indicate that less effective, more realistic Nature-based Solution application levels would have an impact. This can be seen clearly when the link between sediment load reduction and reduction of flooding incidence are investigated. The water level duration curve in Figure 4.17 shows that the number of days the river spills at Buloburde is reduced from 21 to 19. While this is a reduction, the magnitude of the reduction is small compared to the extensive work that would be required to implement the Maximum Bank Protection scenario.

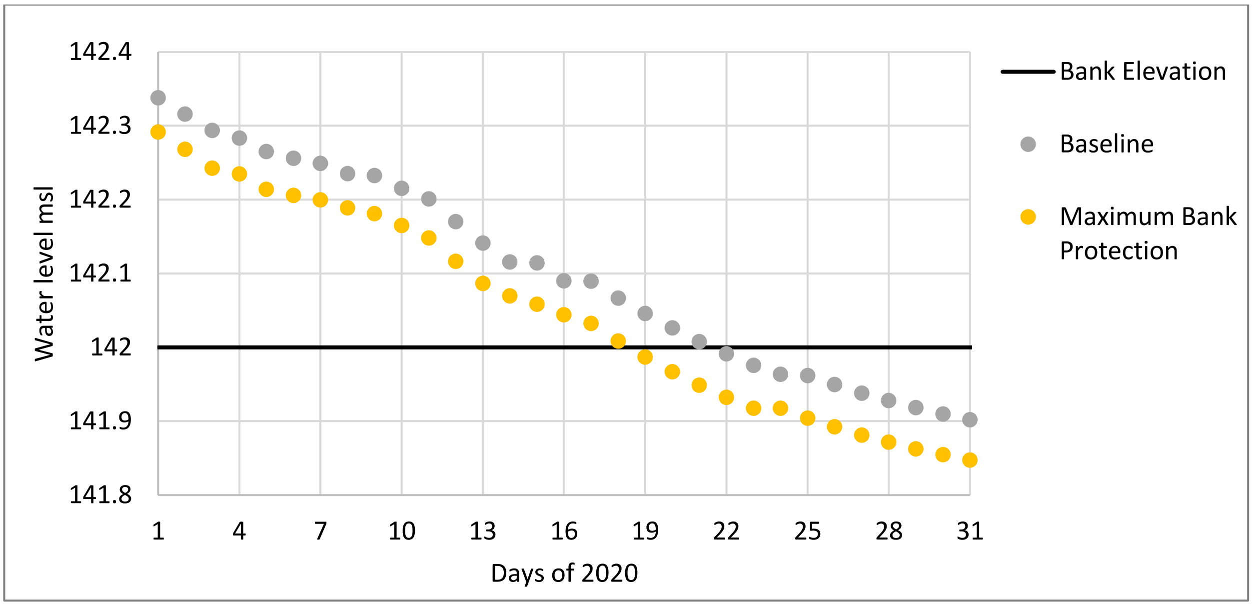


Figure 4.17 Water level duration curve at Buloburde for the baseline and Maximum Bank Protection scenarios.

Nature-based Solutions to stabilize riverbanks have many benefits not related to sediment load reduction, for example to ensure reliable use of the riverbanks as access ways / roads. There are local factors that inform bank stabilisation prioritisation, such as important infrastructure that requires protection or water intake pipes that could risk being silted up with sediment in the event of riverbank collapse. The results from the Maximum Bank Protection scenario show that reduction of the incidence of river flooding is not a factor when selecting or prioritising where to implement Nature-based Solutions for riverbank stabilisation when considering the bigger picture, and rather that this important river management activity can be planned and executed based on other factors.

4.4.2 Topsoil Erosion Reduction in Somalia

The next Nature-based Solution scenarios tested are for topsoil erosion reduction in Somalia as a flood management intervention. The objective of these scenarios is to ascertain the impact of reducing the amount of sediment that enters the river due to topsoil erosion in the Somali part of the Shabelle River catchment on river flooding.

The Nature-based Solutions selected that can reduce the sediment load added to the river due to topsoil erosion are those that either stabilize topsoil in the catchment and prevent erosion from occurring, such as reforestation and revegetation in the catchment, or that prevent eroded topsoil from entering the river, such as sand dams. Gully rehabilitation can work in both ways – sediment that would be eroded from the gullies remains in place, and topsoil eroded from the catchment can be retained in the gully vegetation.

From the perspective of the in-channel sediment transport model, all Nature-based Solutions to reduce topsoil erosion are implemented by reducing the amount of sediment in the soil erosion boundary condition. Three scenarios were tested. The first, “Maximum S. Topsoil Erosion Reduction,” assumes perfect, ideal application, where all soil erosion from the catchment is prevented from entering the river (100% reduction). This is an extreme scenario that would be impossible to execute in reality; however, it is an enormously valuable modelling exercise, because much can be learned about how the Nature-based Solutions for topsoil erosion reduction in the Somali catchments impacts flooding. The second scenario, “Half S. Topsoil Erosion Reduction,” simulates the situation where the topsoil entering the river is reduced by half (50% reduction). The thirst scenario, “Quarter S. Topsoil Erosion Reduction,” simulates the situation where the topsoil entering the river is reduced by one quarter (25% reduction). The scenarios are implemented by decreasing the lateral topsoil erosion sediment boundary by 100%, 50%, and 25% for the entirety of the five-year simulation period (including the warm-up period). The other two sediment boundary conditions – the upstream boundary at Beledweyne and the lateral embankment boundary – remain the same as in the baseline.

The sediment mass balance for the topsoil reduction scenarios and the baseline are displayed in Figure 4.18. The total sediment that enters and that leaves the system is lower compared to the baseline in all three scenarios. In the Maximum S. Topsoil Erosion Reduction scenario, the incoming sediment is reduced by 3.15 million tons, which is only approximately one tenth of the total sediment load in the baseline scenario. However, more sediment exits the system in the Maximum S. Topsoil Erosion Reduction scenario than enters it. The system change in this scenario is negative, which indicates net erosion in the modelled system. In the Half and Quarter S. Topsoil Erosion Reduction scenarios, the amount of mass that remains in the system due to sediment deposition is 0.2 and 0.8 million tons, both much lower than the 1.4 million tons remaining in the baseline. The sediment mass balance results indicate that Nature-based Solutions for topsoil erosion reduction in the Somali catchment can substantially reduce the deposition of sediment in the Shabelle River.

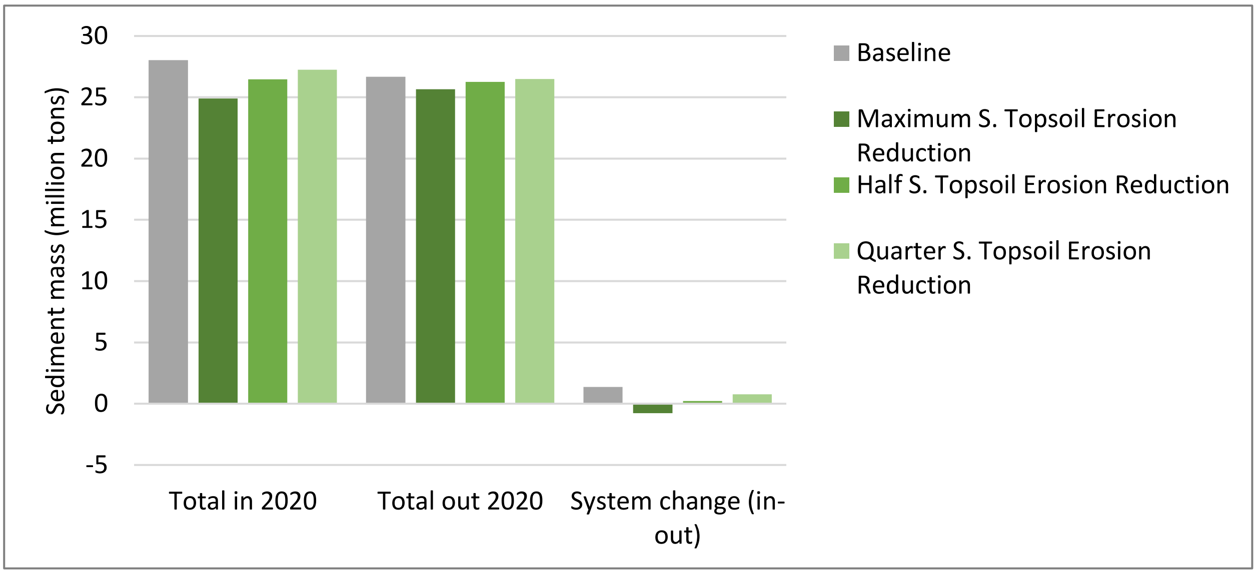


Figure 4.18 Sediment mass balance for the baseline and the three tested effectiveness scenarios of NbS interventions for topsoil erosion reduction in the Somali Shabelle River catchment.

The amount of deposition that has been reduced can be seen in Figure 4.19, which shows the difference in bed level between the baseline and each of the three scenarios. The bed level is on average 20 cm lower in the Maximum scenario than in the baseline, 10 cm lower in the Half scenario than the baseline, and 5 cm lower in the Quarter scenario than the baseline. This is, for the Quarter and Half scenarios, the amount of deposition prevented by application of each intervention for the five-year simulation period.

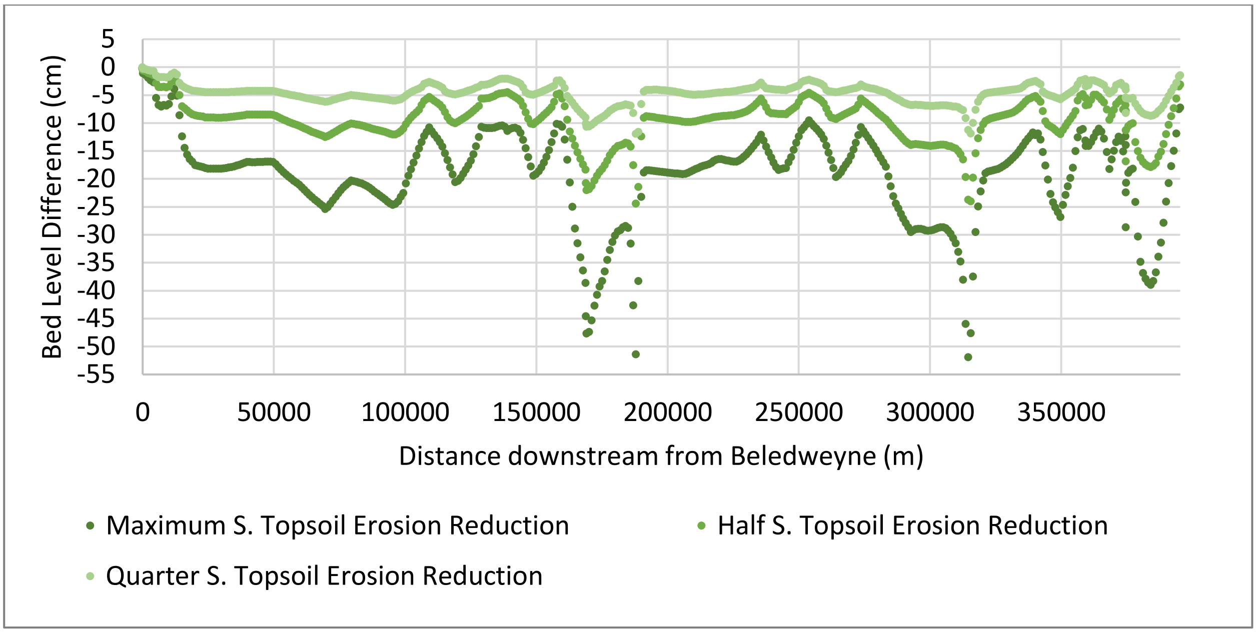


Figure 4.19 Difference in bed level elevation at the end of the simulation period for each computational point between the baseline scenario and each of the three tested effectiveness scenarios of NbS interventions for topsoil erosion reduction in the Somali Shabelle River catchment.

The plot shows the Scenario minus Baseline. Negative values indicate that the bed elevation in the scenario is lower than the bed level in the baseline. Note the unit of the Y-axis is centimetre.

The sediment mass balance and bed level elevation results show that the application of the Nature-based Solutions to reduce topsoil erosion in the Somali Shabelle catchment do substantially reduce deposition in the modelled domain. The water level duration curve at Buloburde (Figure 4.20) shows that this reduction of deposition also substantially reduces the incidence of flooding at Buloburde. In the Maximum and Half S. Topsoil Erosion Reduction scenarios, the water level never reaches the bank elevation, which means that no flooding occurs. In the Quarter S. Topsoil Erosion Reduction scenario, there is flooding for 11 days, reduced from 21 days in the baseline.

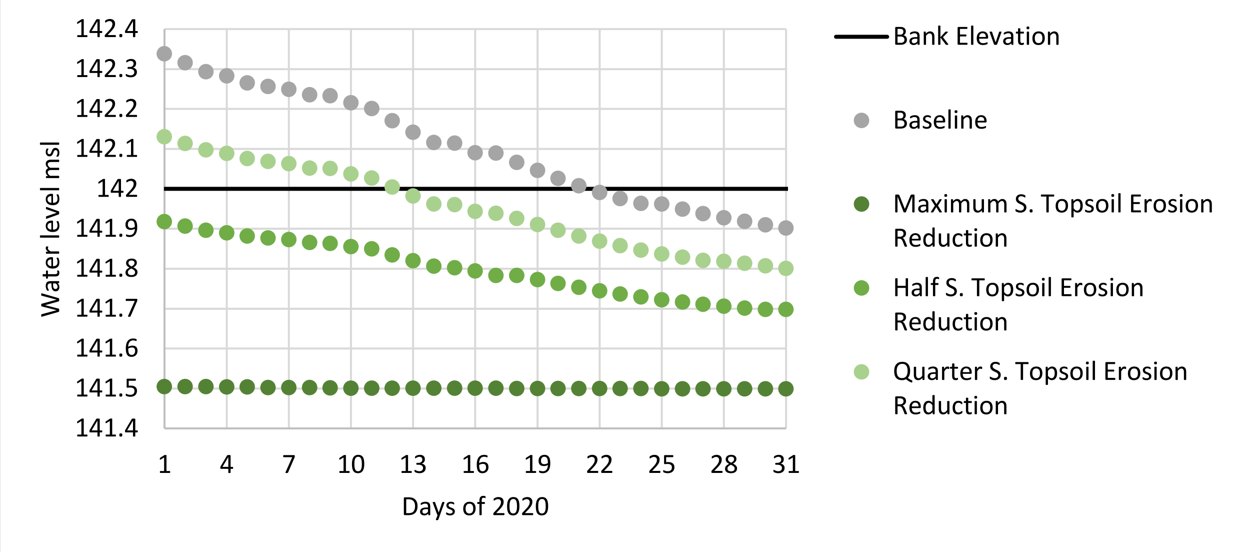


Figure 4.20 Water level duration curve at Buloburde for the baseline and each of the three tested effectiveness scenarios of Nature-based Solution interventions for topsoil erosion reduction in the Somali Shabelle River catchment.

The three scenarios to investigate Shabelle River flooding reduction by application of Nature-based Solutions that reduce eroded Somali topsoil from entering the river show promising results. The sediment mass balance indicates that the net deposition in the river may be drastically reduced by reduction of eroded Somali topsoil inputs. In the Maximum S. Topsoil Erosion Reduction scenario, the extreme, ideal case where no eroded Somali topsoil is modelled to enter the river, the model exhibits net erosion. Both the Maximum and Half S. Topsoil Erosion Reduction cases eliminated flooding at Buloburde. While a reduction in topsoil erosion of 50-100% may not be realistically attainable, these simulations show that interventions targeting topsoil erosion in the Shabelle catchment in Somalia may not be futile and may prove to reduce the incidence of flooding even though this source accounts for only one tenth of the total sediment load in the Shabelle River.

Data limitations prevent further analysis of how much eroded topsoil should be prevented from entering the river to achieve an acceptable flooding incidence reduction. Sediment deposition and erosion dynamics are highly dependent on the sediment grain size, and data on this key parameter is lacking. To obtain more detailed results, is it essential to collect information regarding the sediment grain size and bed composition along the length of the modelled domain and further refine the model.

4.4.3 Topsoil Erosion Reduction in Ethiopia

The last Nature-based Solution scenarios tested are for topsoil erosion reduction in Ethiopia as a flood management intervention. The objective of these scenarios is to ascertain the impact of reducing the amount of sediment that enters the river due to topsoil erosion in the Ethiopian part of the Shabelle River catchment on river flooding. These scenarios investigate the impact of decreasing the amount of sediment that flows across the border from Ethiopia into Somalia on river flooding in Somalia.

As in the previous three scenarios, the Nature-based Solutions selected that can reduce the sediment load added to the river due to topsoil erosion are those that either stabilize topsoil in the catchment and prevent erosion from occurring, such as reforestation and revegetation in the catchment, or that prevent eroded topsoil from entering the river, such as sand dams. Gully rehabilitation can work in both ways – sediment that would be eroded from the gullies remains in place, and topsoil eroded from the catchment can be retained in the gully vegetation.

From the perspective of the in-channel sediment transport model, all Nature-based Solutions to reduce topsoil erosion in Ethiopia are implemented by reducing the amount of sediment in the upstream boundary condition at Beledweyne. Three scenarios were tested. The first, "High E. Topsoil Erosion Reduction," simulates the situation where the sediment carried by the river at Beledweyne is reduced by 30%. The second scenario, "Middle E. Topsoil Erosion Reduction," simulates the situation where the sediment carried by the river at Beledweyne is reduced by 20%. The thirst scenario, "Low E. Topsoil Erosion Reduction," simulates the situation where the sediment carried by the river at Beledweyne is reduced by 10%. The scenarios are implemented by decreasing the upstream sediment boundary by 30%, 20%, and 10% for the entirety of the five-year simulation period (including the warm-up period). The other two sediment boundary conditions – lateral boundaries for topsoil erosion and embankments – remain the same as in the baseline.

The sediment mass balance for the Ethiopian topsoil reduction scenarios and the baseline are displayed in Figure 4.21. The total sediment that both enters and that leaves the system is lower compared to the baseline in all three scenarios. In the High E. Topsoil Erosion Reduction scenario, the incoming sediment is reduced by nearly 7.3 million tons. Because the load at Beledweyne accounts for approximately 90% of all sediment entering the system, the 30% reduction of the upstream source correlates to a 26% reduction of all sediment entering the system. However, the mass of deposited sediment is reduced by only 13% – from 1.4 million tons in the baseline to 1.2 million tons in the High E. Topsoil Erosion Reduction scenario. In the Middle and Low E. Topsoil Erosion Reduction scenarios, the amount of mass that remains in the system due to sediment deposition is similar to that of the High scenario, 1.2 and 1.3 million tons, respectively. This indicates that substantial changes to the sediment load carried by the river at Beledweyne do not correlate to substantial changes in sediment deposition from the overall system perspective.

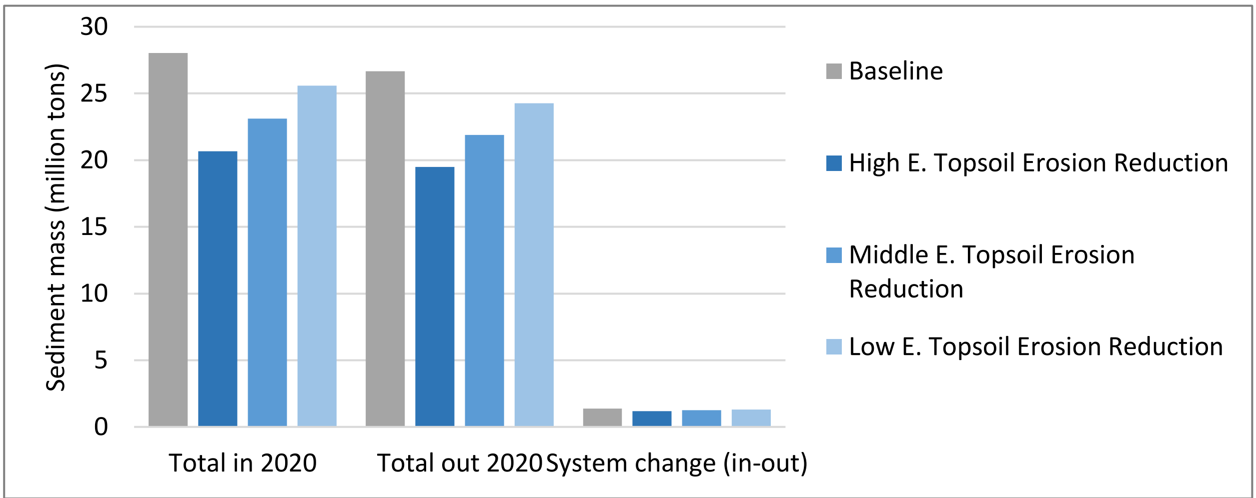


Figure 4.21 Sediment mass balance for the baseline and the three tested effectiveness scenarios of Nature-based Solution interventions for topsoil erosion reduction in the Ethiopian Shabelle River catchment.

From Figure 4.22, it can be seen that most of the changes in deposition between the three Ethiopian topsoil erosion reduction scenarios and the baseline occur within the first 100 km of the modelled domain. The magnitude of the difference in in the first 100km for each of the three Ethiopian topsoil reduction scenarios are not so dissimilar from the magnitude of the changes in the Somali topsoil reduction scenarios, which were seen over the length of the river profile. This indicates that changes in sediment load carried by the river at Beledweyne impact primarily this region, and do not have an effect on deposition along the last 300 km of the river profile.

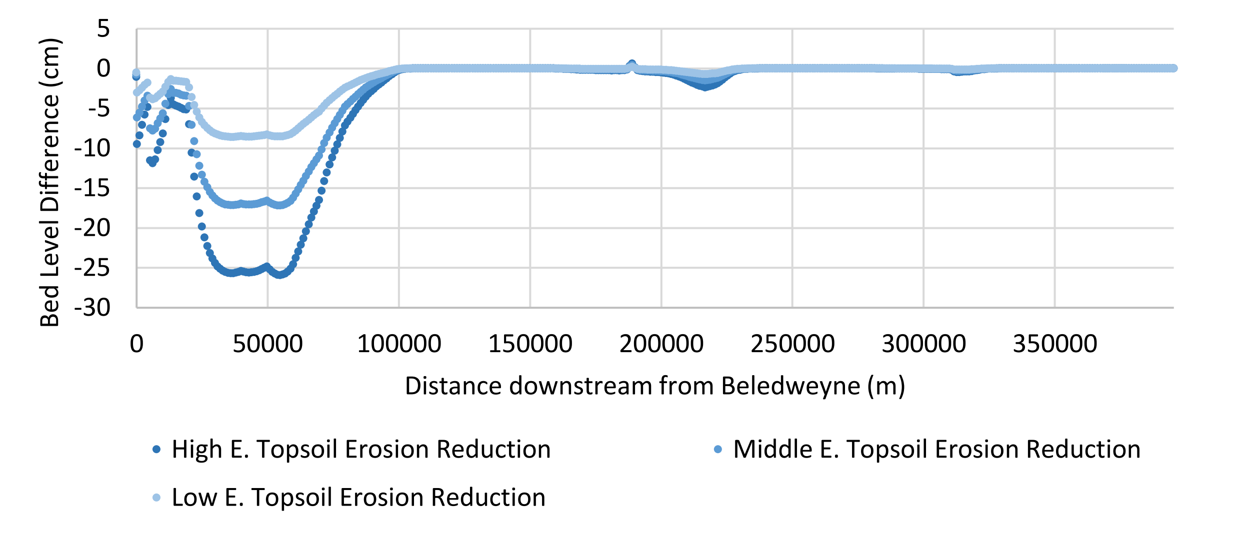


Figure 4.22 Difference in bed level elevation at the end of the simulation period for each computational point between the baseline scenario and each of the three tested effectiveness scenarios of NbS interventions for topsoil erosion reduction in the Ethiopian Shabelle River catchment (Scenario minus Baseline).

Negative values indicate that the bed elevation in the scenario is lower than the bed level in the baseline. Note the unit of the Y-axis is centimetre.

The pattern observed in Figure 4.22 is due to the sand fraction in the inflowing sediment depositing, while the silt and clay fractions remain in suspension and pass through the system. The silt and clay fractions enter at Beledweyne and exit the model system again at Jowhar. The sand in the topsoil from the Somali part of the Shabelle catchment also deposits relatively quickly, while the silt and clay fractions remain in suspension. The difference between these two situations is that the incoming sand from the Somali catchment is distributed along the length of the modelled domain, whereas the sand from the Ethiopian catchment only enters the model at the upstream point.

Flooding is only likely to be reduced in areas where sediment deposition is reduced. In Figure 4.22, the position of Buloburde is indicated along the length of the profile. At this location, there is very little change between the baseline and the three tested scenarios. In Figure 4.23, it can be seen that there is also very little change in simulated water level. Each water level duration curve is so similar to the others, that there are the same number of days of spilling in the baseline and each of the three scenarios. If a location within the upper 100 km had been selected for comparison of flood incidence, it is likely that there would have been a difference in the flooding results.

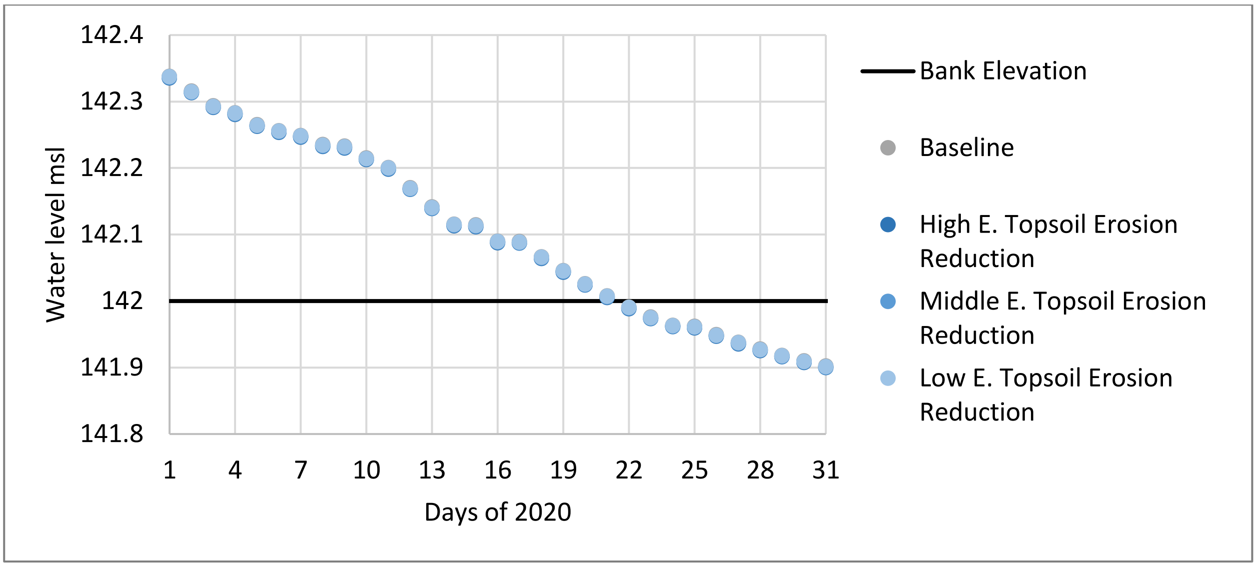


Figure 4.23 Water level duration curve at Buloburde for the baseline and each of the three tested effectiveness scenarios of Nature-based Solution interventions for topsoil erosion reduction in the Ethiopian Shabelle River catchment.

Note that all four series are indeed plotted in the figure, because the values are so similar, the plots appear directly on top of one another.

The three scenarios to reduce the amount of topsoil erosion in the Ethiopian part of the Shabelle catchment show that the sediment carried by the river at Beledweyne impacts only the first 100 km downstream of Beledweyne. This result is dependent upon the grain size of the modelled sediment particles. The silt and sand portions of the incoming sediment remain in suspension and travel through the model domain, while the sand portions of the incoming sediment deposit within the first 100 km. Grain size measurements of the suspended sediment and of the riverbed at Beledweyne are necessary to confirm the model results and are essential to any further refinements to the model.

4.4.4 Sediment Balance Comparison

Figure 4.24 shows the sediment mass balance results for the 2020 baseline and all tested Nature-based Solution application scenarios. The scenario “Maximum Bank Protection” simulates a 100% reduction in sediment added to the river via bank collapse. The scenarios Maximum, Half, and Quarter S. Topsoil Erosion Reduction simulate 100%, 50%, and 25% reductions, respectively, in sediment added to the river via reduction of topsoil from the Somali part of the Shabelle catchment entering the river. The scenarios High, Middle, and Low E. Topsoil Erosion Reduction simulate 30%, 20%, and 10% reductions, respectively, in the sediment load carried by the river at Beledweyne.

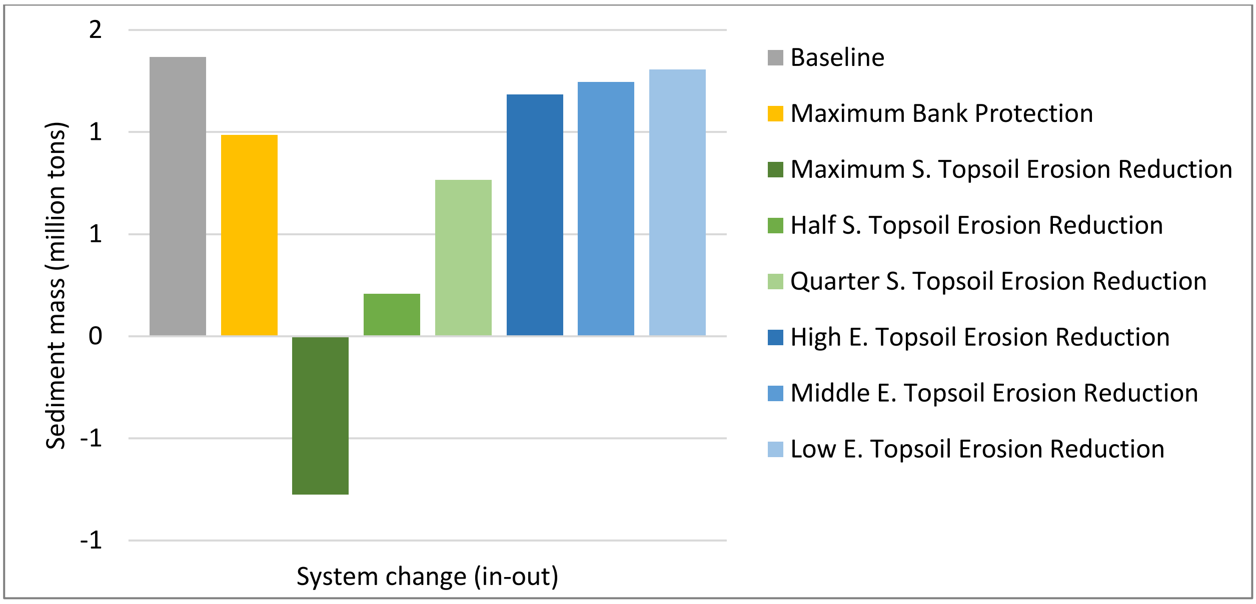


Figure 4.24 System change (Sediment in - Sediment out) for 2020 baseline and all tested Nature-based Solution application scenarios.

The 100% reduction scenarios are valuable, even though they are infeasible, as they yield information about the degree to which the sediment source impacts the system. From the Maximum Bank Protection scenario, it can be seen that the contribution of this source to deposition in is relatively small, as much sediment is still deposited. From the Maximum S. Topsoil Erosion scenario, it can be seen that the contribution of this source to deposition in the system is large. In fact, when this sediment source is removed from the system, the modelled domain becomes net eroding – the river picks up sediment from the riverbed to compensate for the lack of sediment in the system and come into equilibrium. It should be recalled that the assumptions behind the simulations mean that the absolute results are uncertain and that they should be carefully evaluated. However, the relative difference between the scenarios is likely to be representing the effects at a reasonable level.

The Half and Quarter S. Topsoil Erosion Reduction scenarios also demonstrate that changes in this sediment source impact the deposition dynamics of the river, as each show differences to the baseline and to the Maximum S. Topsoil Erosion Reduction scenario. Further refinement of the model is necessary to ascertain the relationship between the degree of reduction of the eroded topsoil sediment source necessary to reduce the incidence of flooding either altogether or to an acceptable level.

The High, Middle, and Low E. Topsoil Erosion Reduction scenarios demonstrate that changes in this sediment source do not have a substantial impact on the deposition dynamics of the river, as they show neither substantial difference from each other nor from the baseline. Instead, the effect of topsoil erosion reduction in Ethiopia is likely to be seen further upstream than at Beledweyne, which is not included in the modelled river reach.

4.5 Conclusions

Due to the data limitations inherent in this study, detailed interpretation regarding sediment transport processes, for example at specific locations and dates, is not appropriate. Nevertheless, the established sediment transport model has been important to understand the sediment behaviour in the Shabelle River. The sediment transport assessment conducted in this study is valuable to determine the overall behaviour and tendencies in the modelled river reach.

From the baseline sediment transport model developed for this assessment, the underlying behaviour of the Shabelle River has been identified. In the modelled stretch of the Shabelle River, from Beledweyne to Jowhar, the primary sediment process is deposition and the process most affecting the locations of bank overflows is also deposition. It was possible to identify that approximately three-quarters of this stretch of river are depositing, and it is these locations where efforts to prevent sediment entering the system could reduce the incidence of river flooding.

It was possible to modify the three modelled sediment sources in the baseline model to test the effectiveness of the application of Nature-based Solutions to decrease the mass of sediment entering the river, decrease sediment deposition, and decrease the incidence of river flooding. Summaries of each of the three tested cases are as follows:

- **Embankment Collapse**: The study concludes that local bank erosion/collapse does not significantly affect the risk for increased flooding elsewhere along the river. The study likewise shows that the impact of reducing sediment entering the river by using bank stabilisation measures has a minimal impact on river flooding. Hence, from the perspective of the river as a whole, bank protection/rehabilitation is not an effective method to reduce flood risk. Nature-based Solutions for bank stabilisation are valuable tools for river management and can be used to protect important infrastructure or ensure that riverbanks can be used as accessways. Addition of sediment to the river and subsequent contribution to river flooding is not a factor to consider during site selection for implementation of bank stabilisation measures.
- **Topsoil Erosion in Somalia**: The impact of reducing sediment entering the river from the Shabelle catchment in Somalia proved to have a large impact on river flooding. Nature-based Solutions for prevention or trapping of topsoil erosion can include reforestation and revegetation of the catchment, sand dams, and gully rehabilitation.
- **River Sediment Load at Beledweyne**: The impact of reducing the load of sediment carried by the river at Beledweyne was shown to impact only the first 100km of the modelled domain. Reduction of load in the river would be accomplished by implementation of measures to reduce eroded topsoil from entering the river in the Ethiopian part of the Shabelle River catchment. Nature-based Solutions to accomplish this are the same as those that could be applied in Somalia, including reforestation and revegetation of the catchment, sand dams, and gully rehabilitation.

5 Climate Change Scenarios

Climate change should be considered when planning, assessing and designing NbS to ensure robust decision making for long-term mitigation of flood and drought impacts under a future changing climate. To understand the impact of climate change on flood peak magnitude, infiltration and the mitigating impacts of the NbS, the hydrological models have been run with climate change scenarios representing a range of possible futures for 2041-2060.

5.1 Future scenarios

The Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report (AR6) from Working Group 1 on the physical science basis of climate change in August 2021. The report shows that human-induced climate change is already affecting many weather and climate extremes in every region across the globe, and there is increased evidence of observed changes in extremes such as heatwaves, heavy precipitation, and droughts.

In the report, a set of five new emissions' scenarios are used to explore the climate response to a range of greenhouse gas, land use and air pollutant futures. The emissions' scenarios cover the range of possible future development of anthropogenic drivers of climate change found in the literature and represent a broader range of futures than was assessed in the previous IPCC Fifth Assessment Report (AR5) published in 2014.

The five emissions scenarios can be understood in terms of a combination of two pathways, the Representative Concentration Pathways (RCPs) which set pathways for greenhouse gas concentrations and the amount of warming that could occur by the end of the century (as used in the previous IPCC AR5 report) and the new Shared Socioeconomic Pathways (SSPs) with a variety of socio-economic mitigation and adaptation challenges that set the stage on which reductions in emissions will – or will not- be achieved.

The five scenarios are named SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 where the first digit refers to the SSP storyline for the socio-economic mitigation and adaptation challenges represented, and the second and third digits are the RCP climate forcing, as described below:

- SSP1-1.9 = SSP 1 and RCP 1.9
- SSP1-2.6 = SSP 1 and RCP 2.6
- SSP2-4.5 = SSP 2 and RCP 4.5
- SSP3-7.0 = SSP 3 and RCP 7.0
- SSP5-8.5 = SSP 5 and RCP 8.5

The SSP storylines are based on narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development (O'Neill et al., 2015, and Riahi et al., 2017) as illustrated in Figure 5.1. SSP2 represents a baseline scenario where the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.

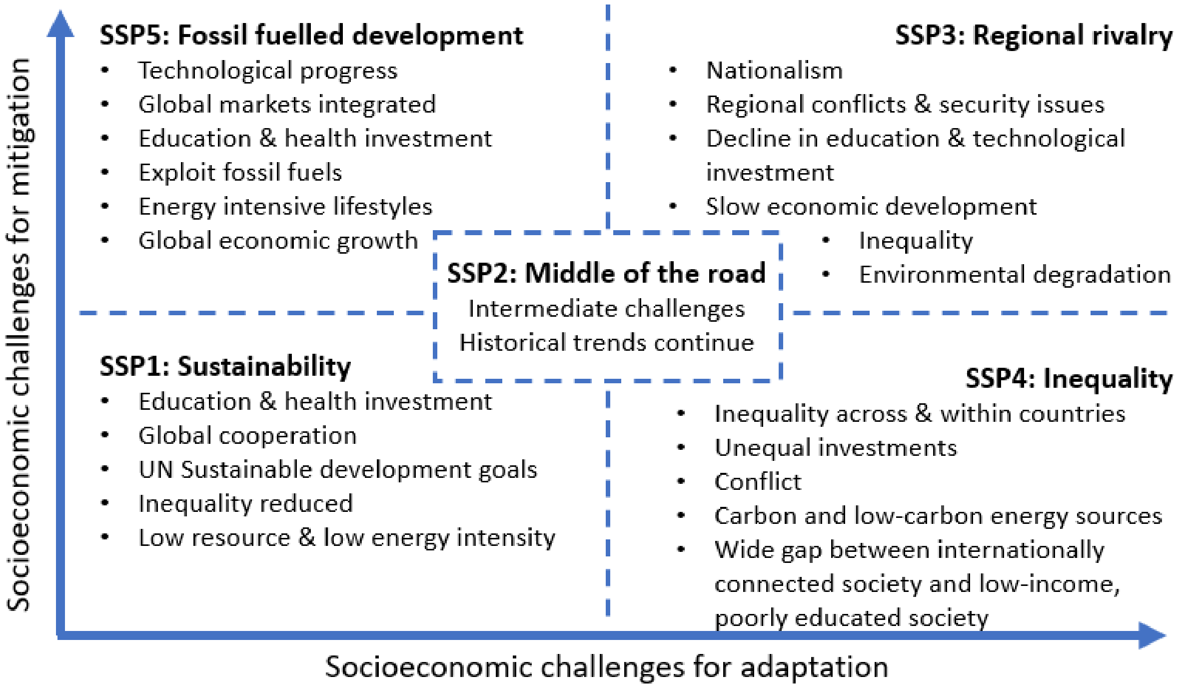


Figure 5.1 A summary of the Shared Socioeconomic Pathways (SSPs) that are used to form the latest IPCC AR6 climate scenarios (O'Neill et al., 2015).

The SSP narratives are combined with the RCP greenhouse gas concentration pathways, and the five resulting scenarios range from scenarios with high and very high greenhouse gas emissions with CO_2 emissions that roughly double or triple (scenario SSP3-7.0 and SSP5-8.5, respectively), to scenarios with very low and low greenhouse gas emissions with CO_2 emissions declining to net zero around 2050 and 2075 (scenario SSP1-1.9 and SSP1-2.6, respectively). A further mid-range scenario (SSP2-4.5) has intermediate greenhouse gas emissions and CO_2 emissions remaining at current levels until around 2050, as illustrated in Figure 5.2.

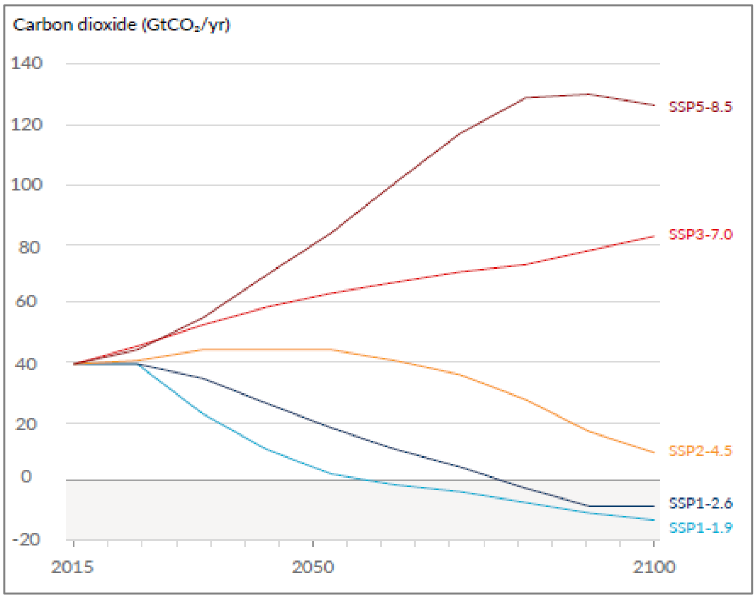


Figure 5.2 Future annual emissions of CO_2 in the five new IPCC scenarios. Future emissions cause future additional warming, with total warming dominated by past and future CO_2 emissions. Source: IPCC AR6 WG1 Summary for Policy Makers Box SPM.1.

A summary of the five scenarios is shown in Figure 5.3. In SSP1-1.9 global warming is limited to less than 1.5 °C meeting the Paris Agreement of limiting global warming to well below 2 °C. Whilst the IPCC AR6 report from August 2021 does not assess the likelihood of the scenarios, SSP1-1.9 is considered unlikely in some studies and is mainly used to inform an assessment of the impacts of meeting the Paris Agreement. SSP1-2.6 is therefore considered a best-case scenario in some studies. In SSP5-8.5 a push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. This scenario is considered unlikely in some studies due to the recent developments in the energy sector towards alternative energy sources.

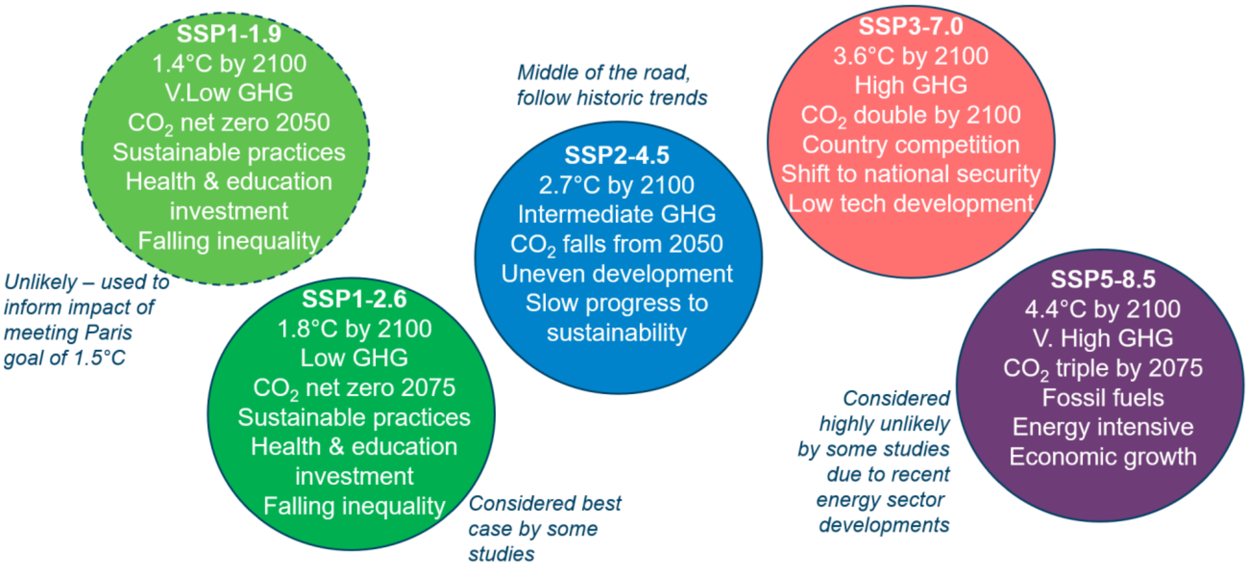


Figure 5.3 Summary of the five emissions scenarios that inform the latest IPCC AR6 report.

To inform the IPCC AR6 report, the set of five scenarios drives climate model projections of changes in the climate system which also account for solar activity and background forcing from volcanoes. Results over the 21st century are provided for the near term (2021-2040), mid-term (2041-2060) and long term (2081-2100) time periods. The climate models used to form the basis of the IPCC AR6 results are from the Coupled Model Intercomparison Project Phase 6 (CMIP6) in which multiple climate modelling groups around the world run global climate models with agreed input parameters.

In this project, we have used the outputs from these global climate models run with the five new emissions scenarios to assess climate change impacts for Somalia.

5.2 Calculation of Climate Change Factors

The CMIP6 modelling group includes over 100 Global Climate Models (GCMs) from over 50 modelling centers around the world. A quality-controlled subset of CMIP6 models and data are made available through the Climate Data Store for users of the Copernicus Climate Change Service[7]. In this project, we used this quality-controlled subset and selected all the GCMs which have the required model output data for all five scenarios. The required data is precipitation and minimum / maximum air temperature, where the air temperature data is then used to calculate Potential Evapotranspiration (PET) using the Kay and Davies (2008) equation.

[7] https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=overview

The GCMs with the available required data for all five scenarios are listed below (note that some models did not contain outputs for SSP1-1.9, but were selected because they contained outputs for all other scenarios):

- EC-Earth3-Veg-LR (Europe)
- CNRM-ESM2-1 (France)
- MIROC6 (Japan)
- GFDL-ESM4 (USA)
- UKESM1-0-LL (UK, South Korea, NZ)
- MPI-ESM1-2-LR (Germany) *(*does not include SSP1-1.9)*
- CCESS-CM2 (Australia) *(*does not include SSP1-1.9)*
- CanESM5-CanOE (Canada) *(*does not include SSP1-1.9)*
- INM-CM5-0 (Russia) *(*does not include SSP1-1.9)*

The outputs from these GCMs were used to calculate monthly change factors for temperature, precipitation and potential evapotranspiration (PET). The GCMs all have similar, but different, spatial resolutions of between 1 and 2 degrees latitude/longitude. The model outputs were, therefore, regridded to match the resolution of the model with the highest resolution so that further calculations could be made at a common spatial resolution of 1 degree latitude and 1.25 degrees longitude.

The temporal resolution of the GCM output data is available at daily and monthly timesteps for a historical time period (1850 – 2014) and a projected time period (2015 – 2100), and monthly data was used in this project as this often provides a better idea of the trends. To calculate the change factors, a baseline period of 25 years from 1990 – 2014 was selected from the historical data and used to provide the static state assumption for the current climate. Future time periods then focused on the same time periods used in the IPCC AR6 report of short term (2021 – 2040), mid-term (2041 – 2060) and long-term (2081 – 2100). Climate change factors were calculated by comparing the mean monthly temperature, PET and precipitation in the future year time periods against the baseline time period for each GCMs run with each of the scenarios.

The result is an ensemble of monthly change factors for temperature, PET and precipitation for each of the five scenarios, where the ensemble members are the different GCMs. These change factors for Somalia are presented in the next section, focusing on the mid-term time period of 2041 – 2060. We have chosen the mid-term time period so that decision making regarding NbS considers mitigating flood and drought impacts for the next three decades rather than just for the shorter-term time period of the next decade. The long-term time period is considered too far into the future to be applicable to the NbS decision making, especially given that climate change uncertainty increases in the long-term.

5.3 Overview for Somalia

The climate change factors for each of the scenarios and time periods are available to view in the portal in the Climate Change CMIP6 datasets. This section provides an overview of climate change in Somalia based on the factors which can be further explored in the portal, and with a focus on Beledweyne where hydrological models have been applied to assess the impact of climate change on flooding, infiltration and the mitigating effects of nature-based solutions.

In SSP2 (middle of the road) scenario, there is an increase in precipitation in both the main rainy sesion (Gu) and the secondary rainy season (Deyr), with a larger increase in the Deyr season. This is shown in Figure 5.4 and Figure 5.5 below which are snapshots of the map and envelope plot from the portal. Figure 5.4 also shows the variability in climate change factors across Somalia, where green shows an increase in rainfall (for example in May in the south of Somalia) and the red shows a decrease in precipitation (for example in May the north of Somalia).

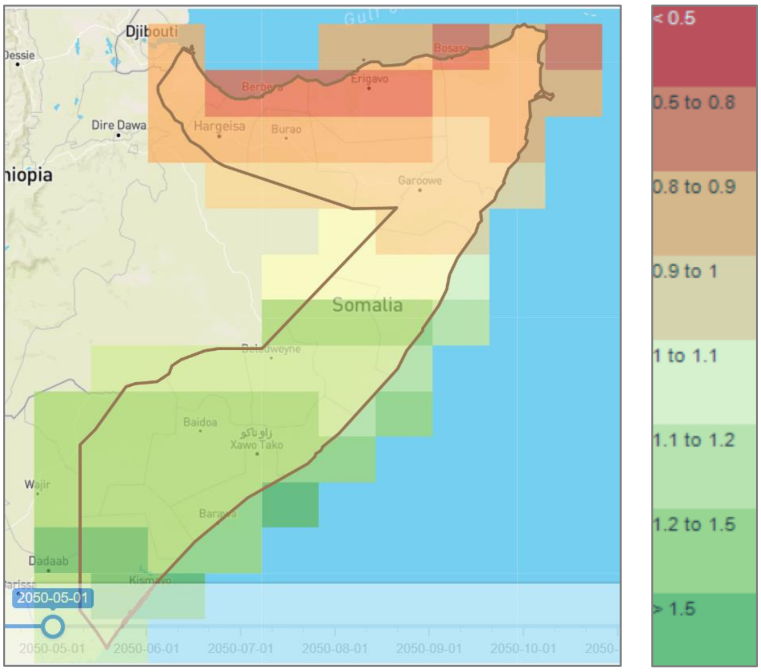


Figure 5.4 **Precipitation delta climate change factors across Somalia in May 2041-2060 in the SSP2-4.5 scenario. Red indicates a decrease in precipitation and green is an increase in precipitation.**

Figure 5.5 is an envelope plot of the ensemble of monthly climate change factors from the different global climate models for Beledweyne. The 25th percentile is the value where 25% of the members are smaller and the 75th percentile is the value where 25% of the members are greater. The most likely outcome is to be found between the 25th and 75th percentile, and the median is the blue line. Factors greater than 1 are an increase in precipitation, and factors below 1 are a decrease in precipitation. In scenario SSP2-4.5, there is an increase in precipitation in Beledweyne in the majority of months.

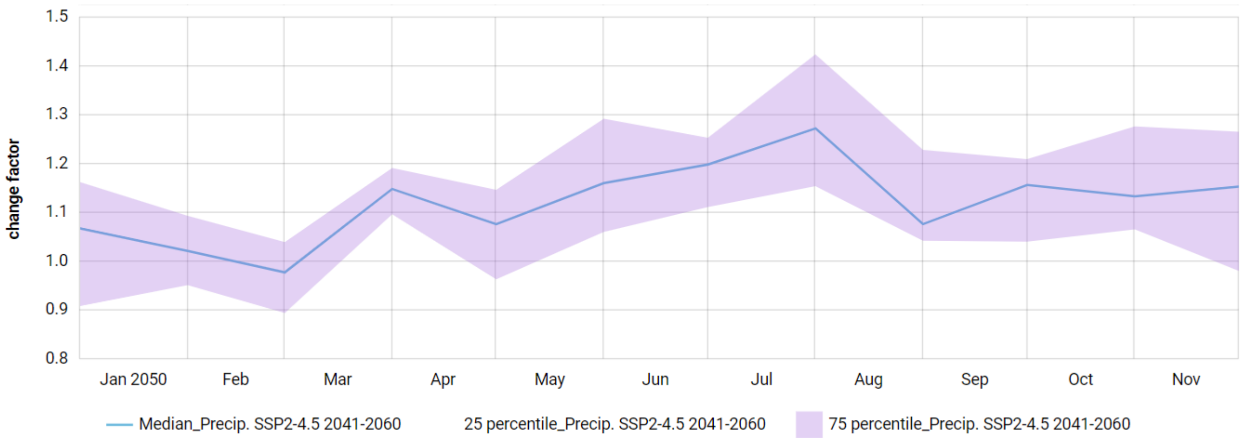


Figure 5.5 **Envelope plot of ensemble monthly precipitation delta climate change factors in Beledweyne in the SSP2-4.5 scenario.**

There is a similar pattern in scenario SSP1-2.6, with an increase in precipitation in both the Gu and Deyr seasons in Beledweyne and a larger increase in precipitation in the Deyr season. This is shown in the envelope plot for Beledweyne in Figure 5.6.

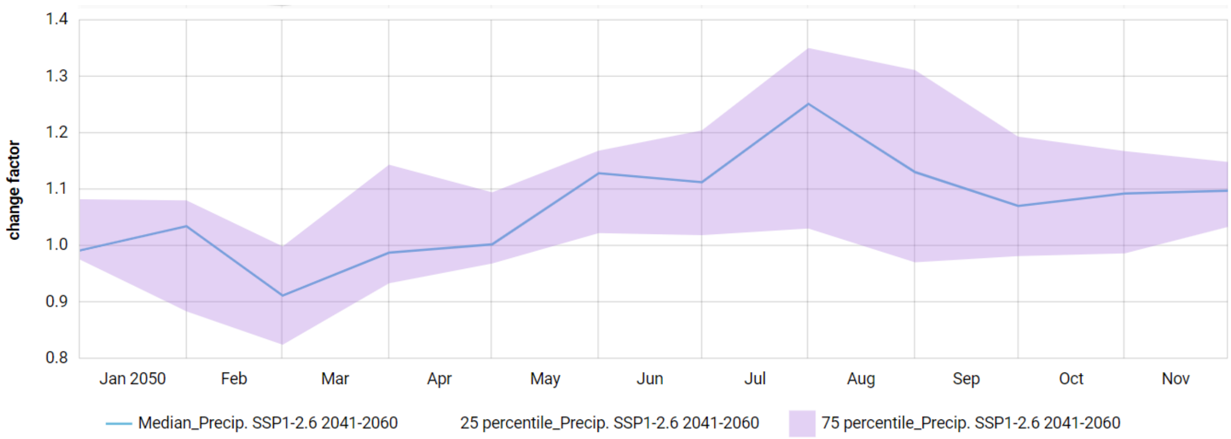


Figure 5.6 **Envelope plot of ensemble monthly precipitation delta climate change factors in Beledweyne in the SSP1-2.6 scenario.**

Scenario SSP3-7.0 shows a different pattern of rainfall change in Beledweyne, with a decrease in rainfall in the Gu season and an increase in rainfall in the Deyr season. This is shown in the maps in Figure 5.7 and in the envelope plot in Figure 5.8.

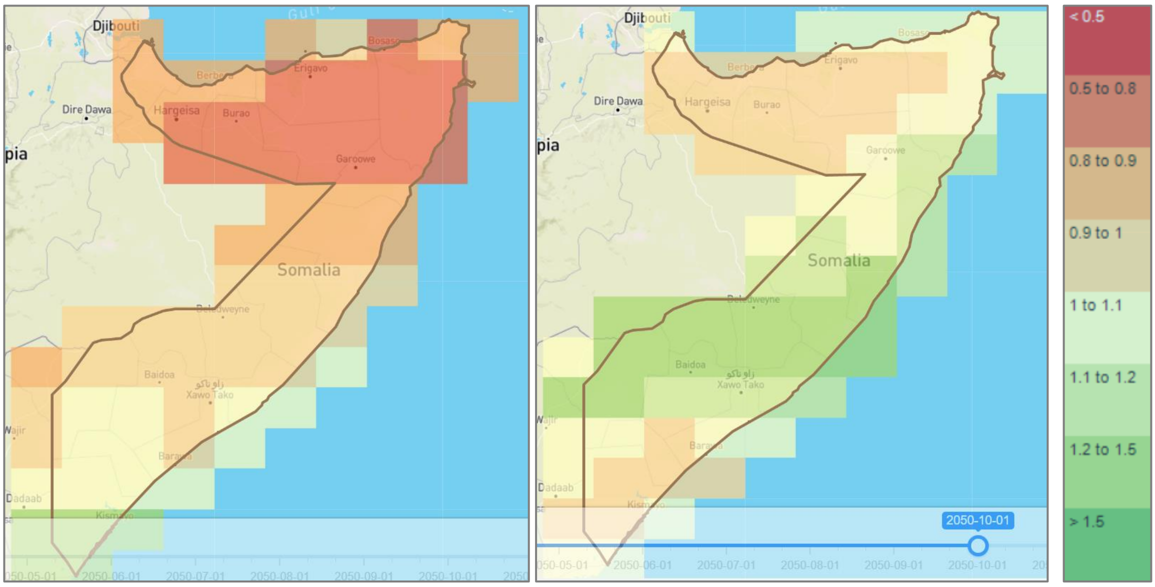


Figure 5.7 **Precipitation delta climate change factors across Somalia: April on the left, and October to the right, 2041-2060 in the SSP3-7.0 scenario. Red indicates a decrease in precipitation and green is an increase in precipitation.**

In summary, rainfall is projected to increase in Beledweyne in the Deyr season in all three climate scenarios and in the Gu season in climate scenarios SSP1-2.6 and SSP2-4.5 but is projected to decrease in the Gu season in climate scenario SSP3-7.0. This is expected to lead to a similar pattern of change in runoff.

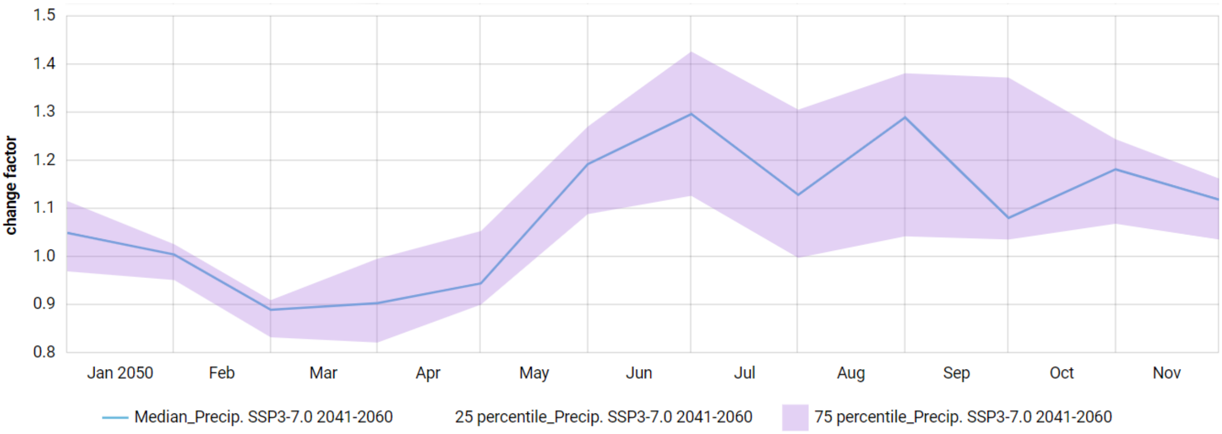


Figure 5.8 Envelope plot of ensemble monthly precipitation delta climate change factors in Beledweyne in the SSP3-7.0 scenario.

5.4 Modelling Approach and Setup

To understand the impact of climate change on flood peak magnitude, infiltration and the mitigating impacts of the nature-based solutions in each of the climate change scenarios, we have applied the climate change factors to the input precipitation and PET timeseries in the hydrological models. As described previously, the factors are an ensemble from nine different GCMs, and it is the median of the ensemble that is applied to the model input timeseries.

The nature of the climate change factors means that it is assumed that the rainfall and PET distribution, or pattern, remains the same in the future and it is just the magnitude that is increased or decreased according to the factor. This is very unlikely to be true, especially for rainfall, indeed the IPCC AR6 report projects an increase in the frequency of heavy rainfall events as well as the magnitude. The hydrological model results, therefore, give an indication of the projected change in magnitude of the flood peak under different climate change scenarios, but it should be noted that the magnitude may further change if the pattern of rainfall changes and flood events may occur more often in the future.

In the Climate Change session of the Physical Workshop on 2nd March 2022 the participants were given an introduction to the IPCC AR6 scenarios and step-by-step exercises to explore the climate change factors across Somalia in the portal. The participants were asked to select which scenarios they thought should be used to model climate change in this project, and the answers were wide ranging across the groups of SSP1, 3, 4 and 5. Of these scenarios, SSP4 is not used in the IPCC AR6 report and SSP5 is considered by some studies to be an unlikely future due to the recent developments in the energy sector towards alternative energy sources. The IPCC AR6 report uses SSP2 as a ‘middle of the road’ baseline scenario of a future where historical trends continue, and therefore we think it is important to also include SSP2 in the scenarios for modelling climate change impacts.

We have therefore selected three scenarios that represent a range of possible futures, SSP1-2.6, SSP2-4.5 and SSP3-7.0, to model climate change impacts in Somalia. The following sections describe the model results and the scenarios are referred to as ‘low’, ‘medium’ and ’high’ in reference to the level of mitigation and adaptation challenges and emissions in each scenario, where ‘low’ is SSP1-2.6, ‘medium’ is SSP2-4.5 and ‘high’ is SSP3-7.0.

5.4.1 Baseline

The climate change scenarios do not affect the two rainy seasons in Somalia equally. For this reason, flood events in both the main rainy season (Gu) and the secondary rainy season (Deyr) have been selected. For the Deyr season, this is the September-October 2009 event which is also the basis for the modelling of different structures in Beledweyne (Section 3.4). For the Gu season, the event in April-May 2016 which is briefly discussed previously has been identified. The climate change investigation focuses on Beledweyne.

The discharge near the downstream end of Xarargagabaale for the Deyr event and the Gu event is shown in Figure 5.9 and Figure 5.10, respectively. There are especially clear differences for SSP3 in the two events. While all climate change scenarios lead to significantly increased discharge during the Deyr event, the SSP3 scenario clearly has the highest discharge during this event. However, during the Gu event, the SSP3 scenario has the lowest discharge during the first, small peak of the event and is almost the same as the current conditions during the second peak.

The SSP2 scenario, which is the second highest during the Deyr event, is the highest during the Gu event. The SSP1 scenario is consistently higher than the current conditions during the Deyr event. In the Gu event, SSP1 is very close to the current conditions during the first peak and clearly higher during the second peak.

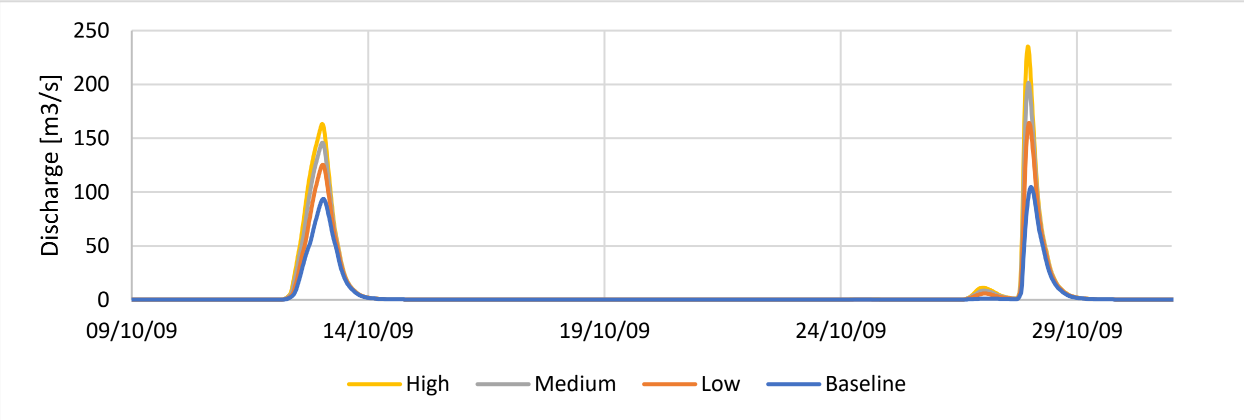


Figure 5.9 Discharge in Xarargagabaale during October 2009 (Deyr) for the baseline model with the current climate conditions and three climate scenarios.

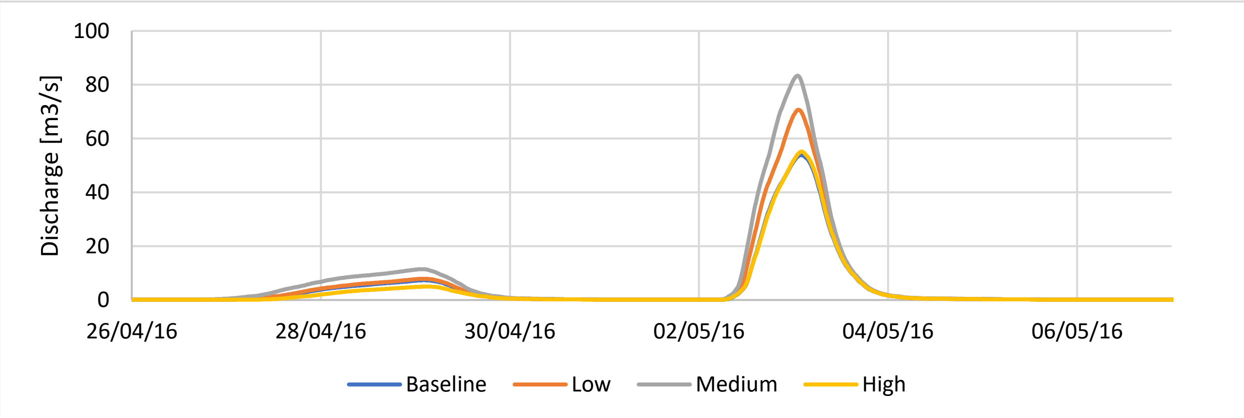


Figure 5.10 Discharge in Xarargagabaale during the April-May 2016 event (Gu) for the baseline model with the current climate conditions and three climate scenarios.

Table 5.1 shows the maximum discharge in both events for the different climate scenarios. This supports the observations above. The increases are generally more dramatic in the Deyr event than in the Gu event, with all scenarios showing significant increases.

Table 5.1 The maximum discharge in the two events in the different climate scenarios.

	September 2009 (Deyr)		April-May 2016 (Gu)	
	Maximum discharge [m³/s]	Percentage of current discharge [%]	Maximum discharge [m³/s]	Percentage of current discharge [%]
Current	104.7	100	53.9	100
Low	164.2	157	70.7	131
Medium	201.7	193	83.4	155
High	235.3	225	55.2	102

5.4.2 Flood Peak Reduction under Climate Change

The models with v-shaped weirs and sand dams have been run under the conditions of the three climate change scenarios described above. These are referred to as structure scenarios (vs. climate change scenarios).

Low emissions scenario

Figure 5.11 shows the flow downstream Weir 2 for the selected structure scenarios for the low emissions climate scenario during the Deyr event. During the first peak, the v-shaped weir delays the flow in the beginning, but as the peak gets higher, it actually has slightly higher discharge than the baseline. During the second peak, the v-shaped weir has some effect on the flood peak reduction, but not to the extent that was seen under current climate conditions. The sand dam has no significant effect on the peaks.

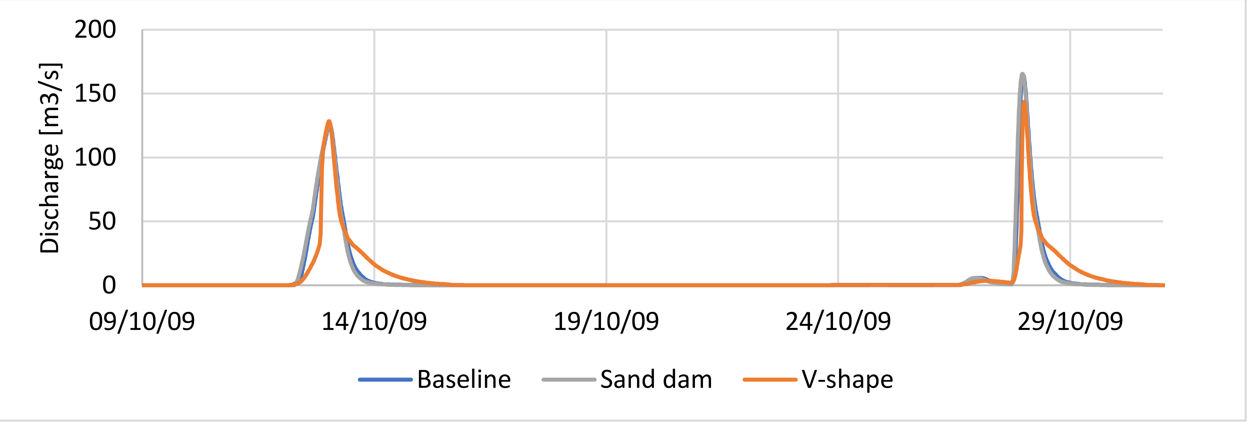


Figure 5.11 Discharge downstream Weir 2 for the baseline model, sand dam scenario, and v-shaped weir scenario, for the low emissions climate scenario during the Deyr event.

Figure 5.12 shows the same results for the Gu event. The effect of the weirs on the first peak is similar to current conditions. The v-shaped weir still has an effect on the second peak but does not reduce it as significantly as it does under current conditions.

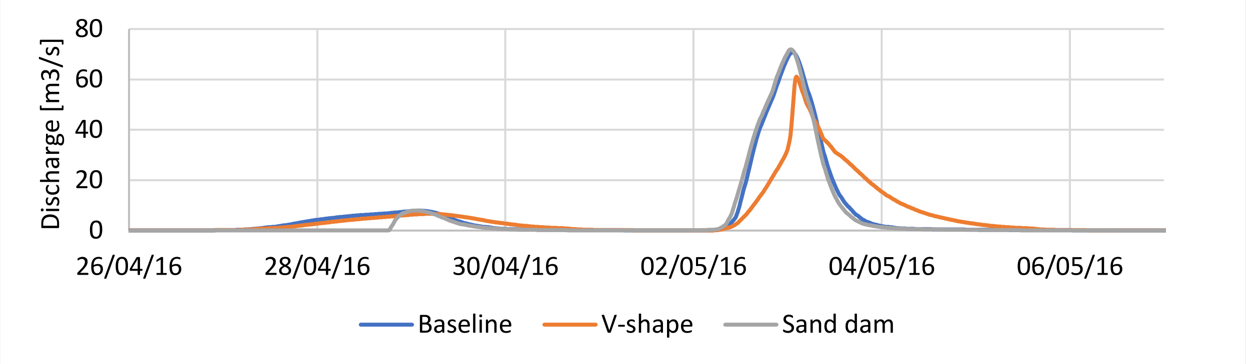


Figure 5.12 Discharge downstream Weir 2 for the baseline model, sand dam scenario, and v-shaped weir scenario, for the low emissions climate scenario during the Gu event.

Medium emissions scenario

For the medium emissions climate scenario in the Deyr event, the relative effects of the different structures are similar to the low emissions climate scenario (see Figure 5.13).

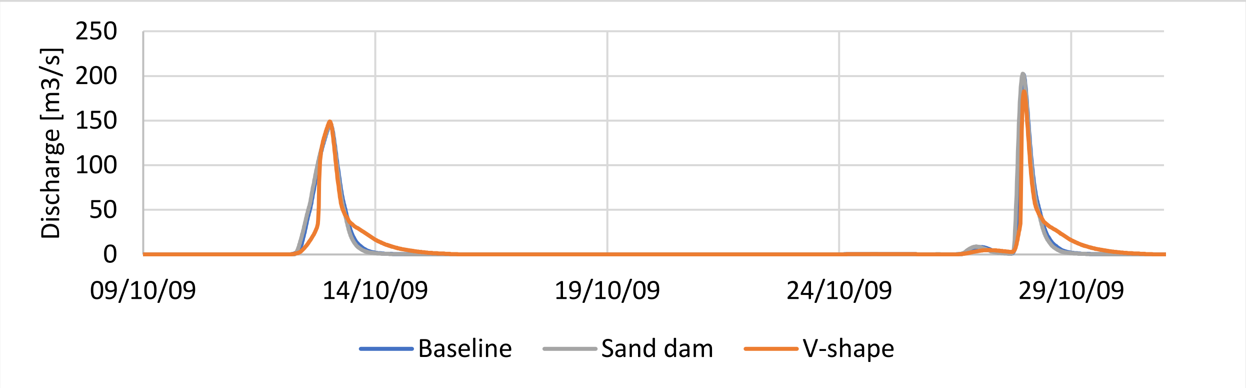


Figure 5.13 Discharge downstream Weir 2 for the baseline model, sand dam scenario, and v-shaped weir scenario, for the medium emissions climate scenario during the Deyr event.

Figure 5.14 shows the results for the Gu event. This diverts more from the low emissions climate scenario than the Deyr event. The sand dam discharge is the same as the baseline in the first peak for a longer period than for the low emissions climate scenario. For the second peak, although the rise is less steep for the v-shaped weir than the other scenarios, the maximum discharge is not significantly reduced.

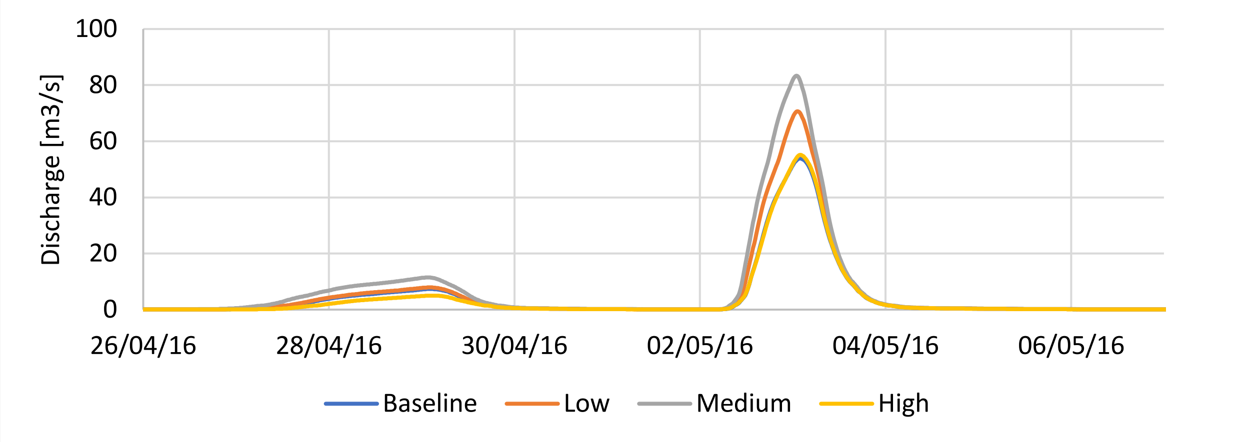


Figure 5.14 Discharge downstream Weir 2 for the baseline model, sand dam scenario, and v-shaped weir scenario, for the medium emissions climate scenario during the Gu event.

High emissions climate scenario

The results for the Deyr event are shown in Figure 5.15. The relative effects of the different structures are very similar to the low emissions climate scenario.

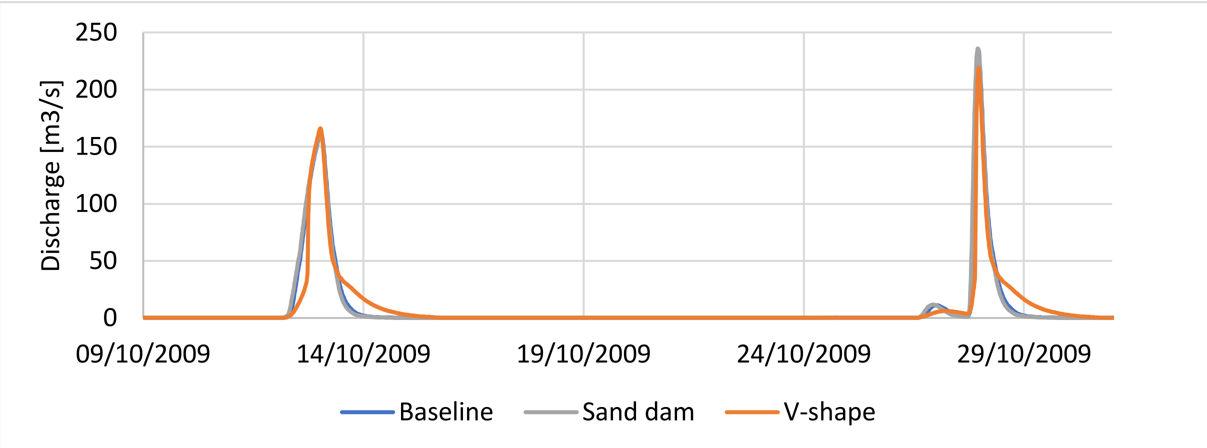


Figure 5.15 Discharge downstream Weir 2 for the baseline model, sand dam scenario, and v-shaped weir scenario, for the high emissions climate scenario during the Deyr event.

Figure 5.16 shows the results for the Gu event. During this event, the first discharge peak is reduced compared to the current conditions, while there is very little change in the second peak. This can be seen in the first peak, where the sand dam holds back the entire peak. During the second peak, the results are very similar to the current conditions.

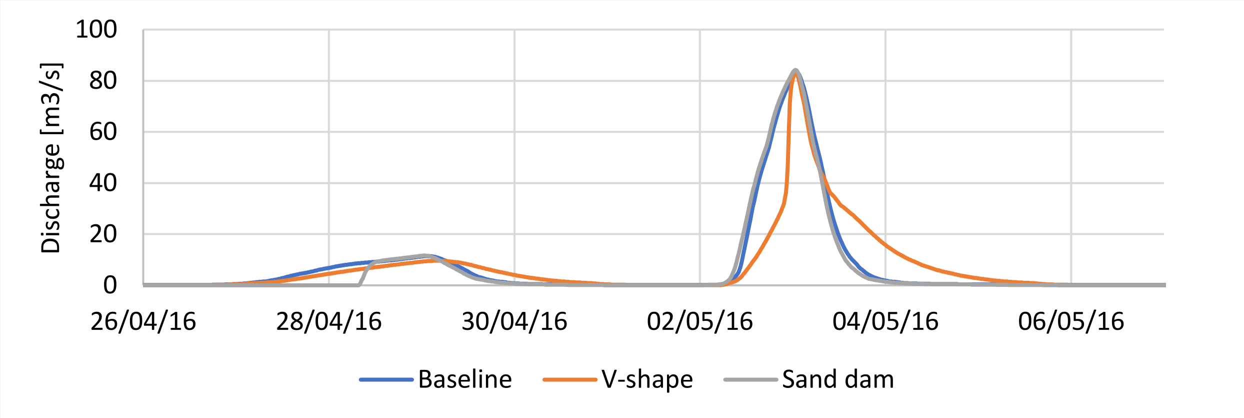


Figure 5.16 Discharge downstream Weir 2 for the baseline model, sand dam scenario, and v-shaped weir scenario, for the high emissions climate scenario during the Gu event.

5.4.3 Infiltration under Climate Change

The estimated daily infiltration for the Deyr event is shown in Table 5.2. In all climate change scenarios, the infiltration increases compared to the current conditions, with the lowest increase occurring for the low emissions climate scenario and the highest for the high emissions climate scenario. This distribution follows the increase in discharge.

Table 5.2 The estimated average daily infiltration (m^3/day) for the selected structure scenarios under the three climate change scenarios and current conditions for the Deyr event.

	Baseline	V-shape	Sand dam	V-shape, percent of baseline	Sand dam, percent of baseline
Current	240	296	727	123	303
Low	254	309	790	129	330
Medium	274	334	808	140	337
High	286	349	818	146	341
Low, percent of current	106	105	109		
Medium, percent of current	114	113	111		
High, percent of current	119	118	113		

The infiltration for the Gu event is shown in Table 5.3. The infiltration does not increase as much as for the Deyr event, and in the high emissions climate scenario it actually decreases.

Table 5.3 The estimated average daily infiltration (m^3/day) for the selected structure scenarios under the three climate change scenarios and current conditions for the Gu event.

	Baseline	V-shape	Sand dam	V-shape, percent of baseline	Sand dam, percent of baseline
Current	238	289	650	121	272

	Baseline	V-shape	Sand dam	V-shape, percent of baseline	Sand dam, percent of baseline
Low	255	309	664	130	278
Medium	283	343	689	144	289
High	227	273	634	115	266
Low, percent of current	107	107	102		
Medium, percent of current	118	119	106		
High, percent of current	95	95	98		

5.5 Sediment transport under climate change

The sediment transport modelling as described in chapter 4 has not been expanded with sediment simulations which consider climate change. The primary reason for this is that the sediment models have only ben applied for within-bank sediment transport calculations. Hence changed flood peaks as a result of climate change would not influence the model results as only flows up to bank full discharge is carried out.

It is likely that increased precipitation due to climate change will lead to increased soil erosion in the future and therefore to a net increase in the inflow of sediments to the Shabelle river. It is likely that the river will be subjected to increased deposition, and therefore also to more frequent overflow spills along the river banks. However, the resulting sediment dynamics in the river is not possible to predict without a model which represents the spilling of water and sediments onto the flood plains. Only then can the export of sediments to the flood plains form part of the analysis, and only then will sediment modelling under climate change scenarios make sense.

5.6 Conclusions

Higher rainfall and runoff are expected for all three climate scenarios for the Deyr season, while there is more variation in the Gu season, with some months experiencing lower runoff in SSP3. There are generally smaller increases during this season than in the Deyr season.

The increased discharge leads to the structures being less effective for reducing flash flood peaks. This may especially become an issue during the Deyr season which has high projected increases in all scenarios.

Increasing the width of the v's in the v-shaped weirs could make them more effective for high discharge events, although it is likely that it will reduce their effectiveness for events with lower discharge as a larger flow will be able to pass through unimpeded. It is recommended that wadis are assessed individually, and the structures designed for events of specific magnitudes at locations, where this type of structure is planned. It is generally recommended that climate change is taken into account when designing these structures.

Climate change is likely to increase the inflow of sediments to the Shabelle river. However, the sediment dynamics under climate change have not been possible to model and therefore verify, as the current sediment model only operates with in-stream flows.

6 Indicators for Planning and Prioritization

Based on desk research and NbS catalogue findings, a set of indicators were identified that can support prioritization of potential NbS for implementation and upscaling within the Shabelle River basin. The selected indicators[8] have been broadly categorized as follows:

- Recommended indicators for assessment of hazard mitigation potential. Selection of indicators that can assist assessment of the efficiency of selected NbS to mitigate flood hazards. For the project purposes and for assisting the work of the national Flood and Drought Task Force, this set of indicators is prioritized.
- Supplementary indicators to inform NbS sustainability. Recommended indicators covering aspects relating to general site suitability, co-benefits, governance, and sustainability of the NbS that may inform long-term planning decisions.

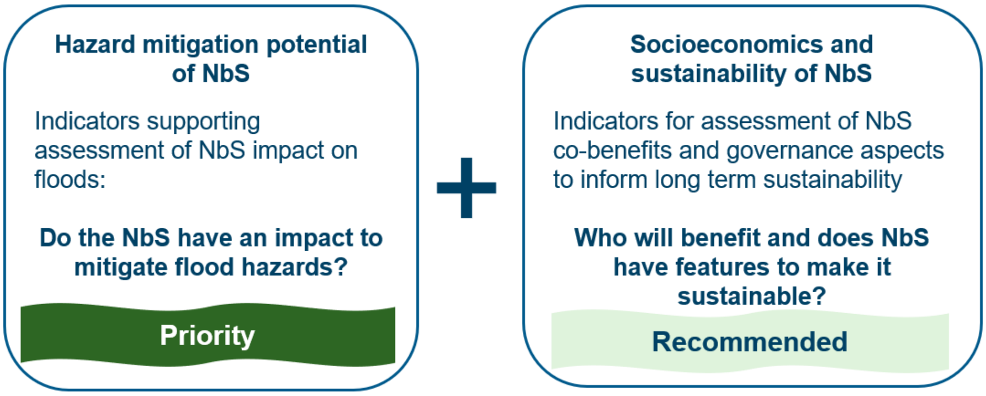


Figure 6.1 Tow broad groups of indicators selected.

Where possible, readily available datasets are proposed for the calculation of the indicators. To assess hazard mitigation potential, selected indicators have been calculated where possible. Where it has not been possible (e.g., calculation requires locally collected data outside the scope of this project), approaches for their calculation are suggested.

6.1 Hazard Mitigation Potential

The aim of calculating indicators for hazard mitigation potential is to assess the extent to which the NbS in question would be able to mitigate flood hazards, and to compare across NbS options based on their efficiency and impact. The focus of the research exercise was to identify which indicators are most applicable in prioritizing the best NbS interventions for flood hazard mitigation in the Shabelle basin. Key considerations include findings of the scenario analyses and data availability.

Due the highly localized nature of flash flooding, it is recommended[9] that indicators for flash flood risk and mitigation assessment include the flash flood's **date and time of occurrence, extent and duration** (assessing the '*flashiness*' or the 'shape' of the flash flood plot against time). Understanding the nature of flash floods can help inform whether the location is a good candidate for employing NbS to mitigate the impact. Such information is most reliable when collected locally,

[8] Given the existing data limitations and the project's focus on floods and drought, this section focuses on a limited selection of recommended priority indicators. Depending on the broader context of NbS implementation in Somalia, other indicators may be added to assist evaluation.
[9] See more details and recommendations under the flash flood mitigation scenario assessment

therefore collection of data is best on site, documenting the flash floods where they occur. For example, during this study, it was found that records of flash floods would only have the year as a time tag, where effort should be made to collect at least the day and duration.

In addition, selected topographic indicators can provide general indication of the catchment response to heavy rains and runoff generation and thus the risk to riverine and flash flooding. Understanding these dynamics can also inform the potential placement of NbS interventions in locations that are known to be at risk to flash floods. Key variables here include slope, soil type, and land cover and land use characteristics of the areas affected by flash floods events.

As established in the Situation Assessment Report, many of the flood events along the Juba and Shabelle rivers are caused by unregulated water intake installations weakening river embankments. Alterations in the natural environment over the past few decades have led to increased erosion which in turn increases sedimentation in river channels, rendering rivers shallower and making it possible for floods to occur even with low amounts of precipitation. Furthermore, sudden embankment failures can locally become an important factor causing flooding although the main sediment related cause for flooding is deposition in the river. Deliberate outlets along the river embankments are made for irrigation during dry seasons.

In this context, NbS can be relevant to address:

- Bank stabilization – to reduce risks of bank collapse and breakages through soil stabilization and soil erosion control measures; change in land management practices and behaviour is also an important variable.
- Sediment control – to improve sediment management, which may create sediment and silt accumulation further increasing risks of flooding.
- Reduction of soil erosion and soil degradation – factors which may exacerbate risks of flash floods and soil stability in embankments.

Better understanding of the flood risk locations is vital to evaluate the potential for NbS application for flood mitigation. This includes understanding the flood extent, flood duration, flood flow dynamics and underlying causes of the floods. Such information is currently available only partly.

A set of key indicators has been identified that can help inform NbS application for flood mitigation. A potential simple indicator framework that can help support planning and prioritization is included below.

Indicator framework in support of NbS planning and prioritization

Placement	Hazard	Socioeconomics	Sustainability
Slope	Maximum flow/duration	Number of beneficiaries	Conflict risk
Soil type	Change in discharge	Vulnerability indicators	Community involvement: planning
Land use, land cover	Sediment deposition	[Land tenure]	Community involvement: implementation
[Invasive species]	NDVI	[Cost of implementation]	
Breakage points			
Flash flood indeces			

Figure 6.2 Example indicator framework for NbS planning and prioritization support, for the instances '[indicator]' no information is available.

The selected indicators and their application is summarized in the table below. Where possible, indicator data have been included in following sections. Where data are not readily available, potential or suggested data sources have been indicated in the proceeding sections.

Table 6.1 Indicators to inform planning of NbS for flood mitigation, Placement and Impact.

Placement		
Indicator/unit	Explanation	Data
Slope (degrees)	Slope points to the prevailing runoff dynamics, where generally speaking communities and assets in the lower lying areas would be most exposed to flood damage. The steeper slopes (in combination with other factors) may also require NbS for stabilization.	Slope can be computed from SRTM Digital Elevation Model (DEM) at 30 m resolution. Data are available.
Soil type (unitless)	Soil type data. Soils with lower infiltration rates can increase risk of flash floods. Soil type data are also required to assess the suitability of soil for the specific interventions (e.g. for selection of appropriate species of NbS for the particular location). A qualitative indicator could be developed when assessing specific sites or NbS – e.g. scale of 1-3 (not suitable to highly suitable).	Soil map from SWALIM is readily available.
Land use and land cover (LULC) (unitless)	Prevailing land use and land cover can indicate both the susceptibility to flash flood risk and location suitability for NbS interventions.	Land cover and land use data are available for the basin from SWALIM.
Invasive species: *Prosopis juliflora*	Presence of the invasive species *Prosopis juliflora* at any potential NbS site can indicate potential risks for the success of the selected vegetation or trees for reforestation, revegetation activities.	Existing maps combined with site observation, local information and earth observation-based mapping.
Embankment breakage points	Information on embankment breakage points along the river can be helpful to understand and prioritize sites where the risk of overflows and bank breakages is already high. Understanding the nature of breakages is especially important to assess the potential for reducing the risks through NbS.	SWALIM produces regular updates and spatial information on the status of embankment breakage points seasonally for the Juba-Shabelle rivers.
Flash flood potential indicators	Flash Flood Potential Index (FFPI), the Height Above Nearest Drainage point (HAND), the use of Global Precipitation Measurement (GPM) 30-minute GPM-Early data product,	Data are available as layers in the portal. See Final Report on flash floods research produced by the project.

Placement		
Indicator/unit	Explanation	Data
	and the morphometric approach. It was not possible to draw conclusions on their applicability due to lack of data.	
Measuring impact of NbS		
Maximum flow/duration (m^3/s/hours)	Indicator to help assess 'flashiness' of the floods. It informs which flash flood risk locations might benefit most from NbS (particularly focusing smaller water storage structures such as sand dams). Generally, locations with shorter term spilling could have potential for higher NbS impact in flash flood prevention/mitigation.	Data collected from flash flood sites recommended and most accurate, given the highly localized nature of the events.
Change in discharge at vulnerable locations (% reduction or increase)	As an indicator, the change in discharge is important for monitoring of the impacts of NbS on flood mitigation over time.	Modelled results (unless gauging station or radar data available).
Sediment deposition (or change in deposition over time) (m)	Changes in sediment deposition depth at selected cross sections over time inform sites where sediment accumulation can exacerbate flood risk. The indicator can also be used to monitor change over time after NbS implementation to measure NbS efficiency in terms of sediment control.	Sediment deposition (or change in deposition over time). As actual sediment depth measurements are typically not possible, the change of maximum depth of river is used as a proxy indicator – where the sediment depth is derived as the difference between riverbed levels resulting from cross sections measurements at different times. Increasing 'shallowness' of the river at a given location here indicates build-up of sedimentation.
Normalized Difference Vegetation Index (NDVI) (scale)	NDVI indicates the greenness of the vegetation. High NDVI values represent dense vegetation while low NDVI values indicate bare soils and increasing flash flood risk.	Data are available from global datasets, also on the project data portal.

6.1.1 Available Data for Calculation

Maximum flow / duration (m^3/s over time in hrs)

Currently the data on the behaviour of flash floods, including their exact location, duration, and spatial extent are largely unavailable from local records in Somalia. Most information stems from news or local observations, which do not capture the needed information systematically.

Due to the rapid nature of flash flood onset, effective real time monitoring and warning is challenging using exclusively satellite based data sources. Expansion of radar capabilities for precipitation estimated and nowcasting in at-risk areas could improve the forecasting and effective management of flash floods considerably. In addition, collection of local observations and community knowledge on local flood characteristics is recommended to improve forecasting and NbS placement accuracy.

When it comes to the NbS potential (or impact), the locations with the shorter-term spilling are likely to have highest potential for making a change via NbS-based interventions (e.g. establishing water storage areas or structures, such as sand dams).

A useful indicator is **% change in the maximum flow and duration**, either simulated for the purposes of potential assessment, or as observed monitoring data for the purposes of assessing impacts of already established NbS. Based on the % change from baseline (which must be established), the indicator can help assess the potential and success of NbS to mitigate flash flood hazards.

See scenario analysis in section 3 for more information on the estimated impacts of selected NbS using modelling approaches.

Change in river discharge (m^3/s) and runoff (m^3/s) at vulnerable locations (% reduction or increase)

Measuring impact of NbS on discharge and runoff over time is key in understanding efficiency of the interventions and informing upscaling at basin and country scale. As an indicator, the change in discharge is therefore important for monitoring purposes. Data its calculation can rely on modelled results, but gauging station or radar data offer higher degree of certainty.

Similar to the previous example, as an indicator, the values could be assigned based on **% change in runoff and discharge at key locations** - either simulated for the purposes of potential assessment, or as observed monitoring data for the purposes of assessing impacts of established NbS.

Change in runoff based on application of various NbS has been modelled as part of the project. See sections 3, 4 and 5 for details on the modelled results.

Slope (degrees)

Slope points to the prevailing runoff dynamics, where, generally speaking, communities and assets in the lower lying areas would be most exposed to flood damage. The steeper slopes (in combination with other factors such as land cover and soil type) may also point to the potential sites for NbS implementation as a measure for runoff speed reduction, soil stabilization or for creating temporary water storage structures.

Slope can be computed from SRTM Digital Elevation Model (DEM). Satellite based 30-metre resolution DEM data of Somalia, as well as the Juba Shabelle basin are available from the Shuttle Radar Topography Mission (SRTM) of the National Aeronautics and Space Administration (NASA)10. Another option is to the Copernicus Digital Elevation Model (DEM) with global coverage at 30-meter resolution (GLO-30).

Slope steepness alone cannot indicate flash flood prone areas and should be viewed in the context with other indicators such as rainfall, soil, land cover, etc. characteristics. For more information on flash flood hazard risk identification, see the Flash flood risk indicator.

[10] NASA, https://www2.jpl.nasa.gov/srtm/

However, for sites with known flash flood occurrences and risks, the slope might indicate favorable locations for NbS interventions that may e.g. help stabilize the slopes or slow down runoff.

Soil type (unitless)

Understanding soil type in areas exposed to floods or flood risk is useful for hydrological modelling and flash flood indices, among many other applications. For example, soils with lower infiltration rates can increase risk of flash floods.

Soil type data are also required to assess the suitability of soil for the specific interventions - e.g. for selection of appropriate species of NbS for the particular location.

FAO-SWALIM has conducted numerous surveys of the soil in different parts of Somalia which has resulted in the compilation of a national soil database for Somalia. Another source is the Global Soil Regions map, based on a reclassification of the FAO-UNESCO Soil Map of the World combined with a soil climate map. The soil map has a distribution of 12 soil orders according to Soil Taxonomy by the US Department of Agriculture's "Global Soil Regions Map"[11].

Combined with information on species and suitable growing conditions, the soil map can be used to inform species selection, amongst other NbS planning aspects. SWALIM soil database also includes assessment of limitations of the various soils in relation to productive agricultural use, which can also inform decisions on tree and vegetation cover choices. The overview of recorded limitations for the Juba-Shabelle basin can be seen below.

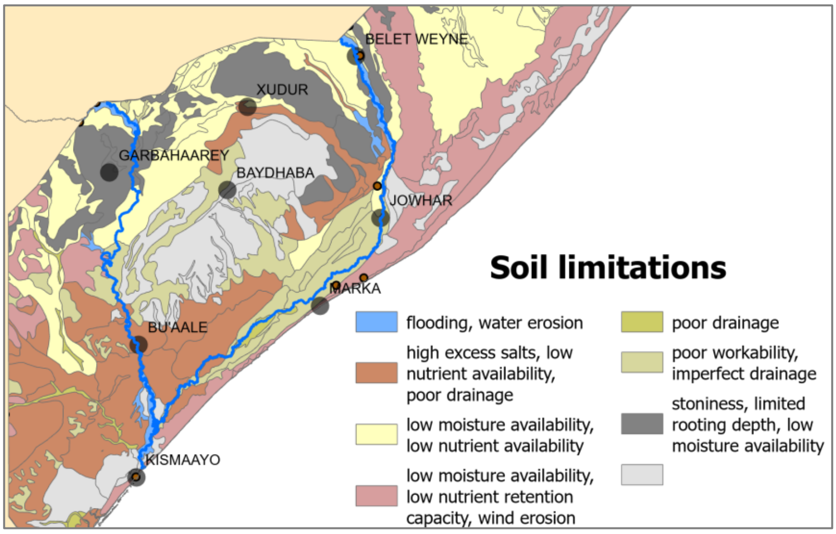


Figure 6.3 Soil limitations (to agricultural activity). Source: SWALIM.

For assessment of feasibility of NbS or comparing various options, the soil properties could be converted to a **qualitative indicator – e.g. on a scale of 1-3 (not suitable – reasonably suitable – highly suitable)** for the species or other type of NbS intervention in question. A more in-depth assessment of the soil requirements is necessary to establish threshold values (e.g. soils suitable for stone or earth bunds may be unsuitable for some revegetation activities and vice versa).

Land use and land cover (LULC) (unitless)

Satellite-based land cover data for Somalia are available from the Copernicus Global Land Service (GCLS) managed by the European Commission, and comprises 100 m global land cover maps,

11 For more information: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054013

covering 2015-2019. Further, more detailed land cover data are available for the Juba-Shabelle basin from SWALIM. Data provide a more detailed overview of current land uses and tree and shrub cover.

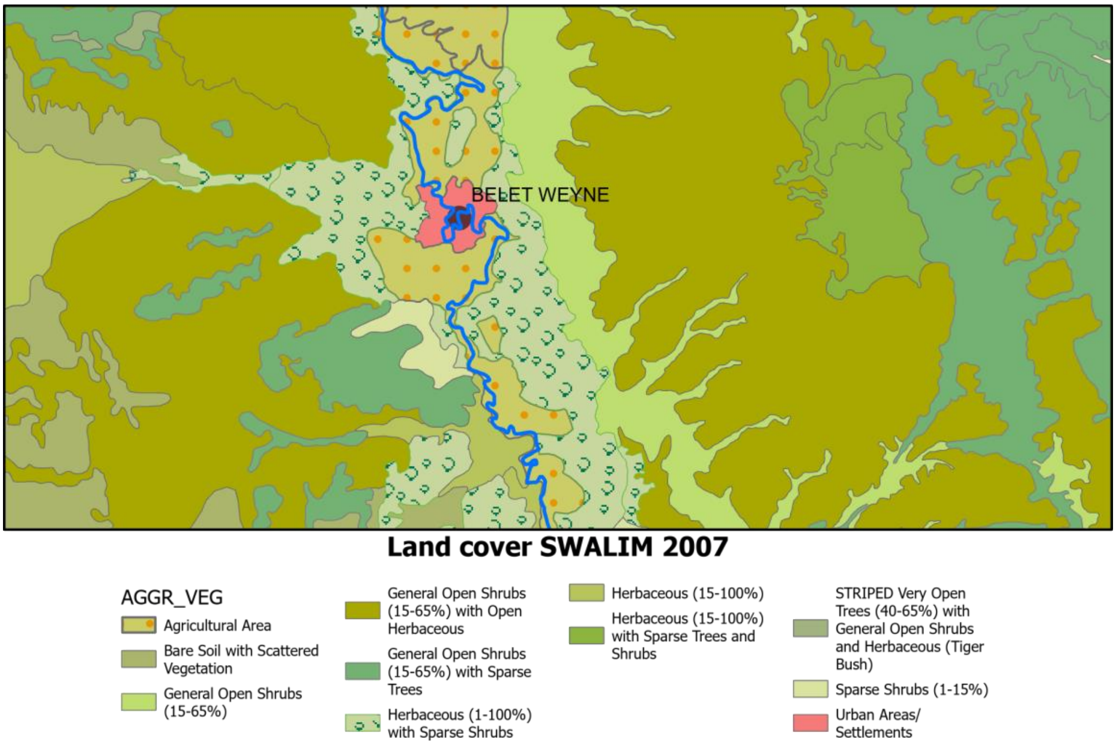


Figure 6.4 Land cover data example containing information of prevailing land use and land cover (area surrounding Beledweyne). Source: SWALIM.

Land cover information can help screen areas that may be suitable for NbS interventions to compare or prioritize points and areas of interest for NbS. Depending on the NbS site, the land use data can inform of e.g. if the area is already in active use for purposes that might collide with NbS (e.g. areas under active agricultural cultivation may not be suitable for larger scale reforestation activities). Similarly, land use data may indicate where the local conditions may be suitable for the NbS in question – e.g. areas where there already is a shrub and tree cover, are likely suitable for expanding these types of activities.

Given the relatively coarse nature of the data, this information is likely most suitable for initial screening, which can then be supplemented with local feasibility analysis, also taking into consideration other variables such as soil, governance, etc.

Sediment deposition (meter depth and depth change at selected locations)

Changes in sediment depth at selected sites over time can help inform sites where sediment accumulation can exacerbate flood risk. Sediment is considered to contribute to an exacerbated flood risk as it raises riverbed levels (due to deposition of sediments).

An indicator can be deployed to inform of sites at risk (where sediment accumulation is causing river overflows) or to monitor NbS impact (observed or modelled). In the latter case, it would be used to monitor change over time after NbS implementation, to measure NbS efficiency in terms of sediment control for sites at risk, by monitoring **change in sediment deposition (in riverbed) in meters**.

Typically, sediment depth measurement is derived as the difference between riverbed levels resulting from cross section measurements at different times. Measuring the elevation of the riverbed, then relating it to the elevation of the riverbanks can help measure the maximum river depth.

Obtaining data on observed bank elevation along the river, or along certain reaches that are known to be vulnerable, or at the actual locations where banks are collapsing is therefore helpful to support sediment analysis. (Regardless of the reasons of riverbank collapse, lowered riverbanks (due to the collapse) are likely increase the risk of flooding at these locations). If such observations in the field are not possible, then identifying locations of bank collapse (e.g annually) could be used as temporary proxy data until more detailed sediment data are available (see indicator on embankment breakages).

Currently complete information on sediment deposition change is not available to the extent that indicator values can be calculated. However, sediment modelling exercise has identified that 70% of the Potential Overflow sites (see SWALIM data and indicator on embankment breakages) on the channel are in depositing sections, 30% are in eroding sections. Similarly, 70% of the Overflow sites are in depositing sections, 30% in eroding sections. It is also in these depositing sections that sediment monitoring would be recommended.

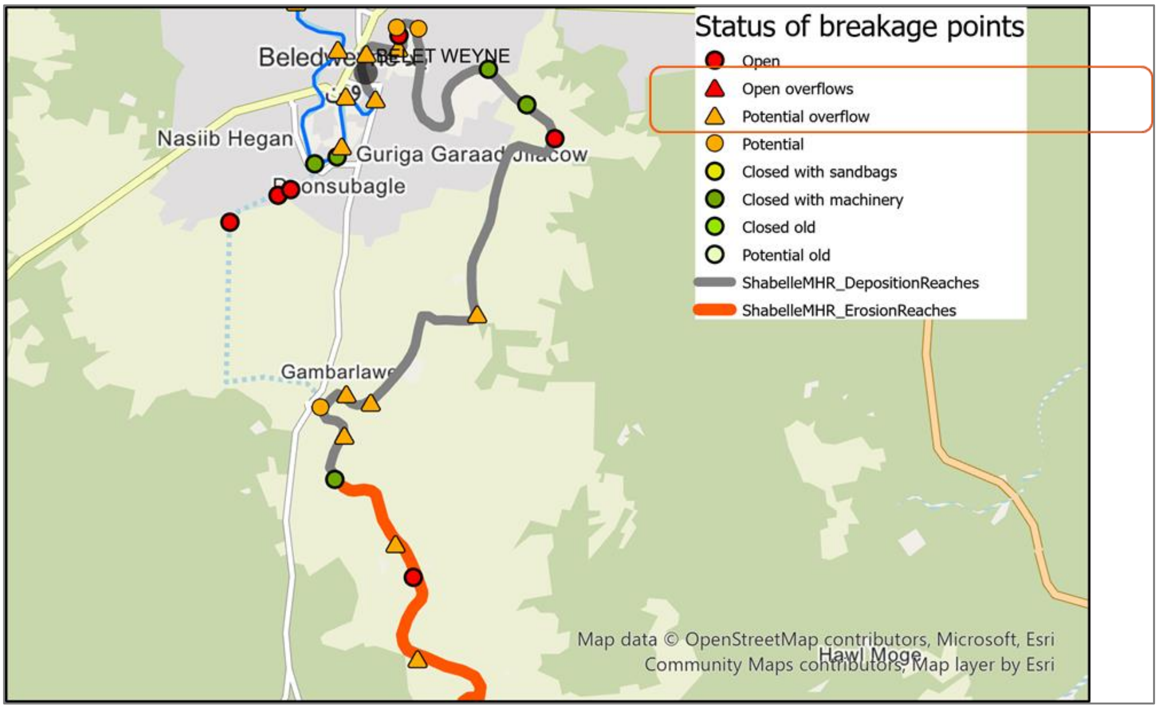


Figure 6.5 Analysis of location of overflow points (SWALIM data from February 2022) in relation to depositing and eroding reaches based on sediment transport model results (snapshot).

These sites should be prioritized for further NbS potential assessment in relation to sediment, bank erosion and stabilization control.

See scenario analysis in sections 4 for sediment transport modelling results and more in-depth assessment om dynamics relating to sediment transport in the rivers.

Normalized Difference Vegetation Index (NDVI)

NDVI is the Normalized difference vegetation index (NDVI). Data for NDVI are available from by MODIS (MOD13C1) vegetation index, which is produced on 16-day intervals and at multiple spatial resolutions.

At a planning stage, identifying areas where negative change in vegetation cover is identified (for comparable time periods over time) could help identify sites where revegetation and reforestation activities can be focused (in combination with assessment of other indicators). Once NbS activities at selected sites and areas are piloted or implemented, NDVI as an indicator can support assessment of the implementation success of particularly revegetation and reforestation projects.

Embankment breakage points

Information on embankment breakage points along the river can be helpful to understand and prioritize sites where the risk of overflows and bank breakages is already high. Understanding the nature of breakages is especially important to assess the potential for reducing the risks through NbS.

For example, where the breakages occur as a result of intentional human behaviour (e.g. river breakages caused by the riverine communities attempts to extract water for livelihood activities during the dry season), the potential of NbS will remain until the underlying causes of the breakage are addressed. In this case, better alternatives to local communities to those of breaking embankments need to be provided.

SWALIM provides regular data on the status river breakage points, along with descriptive information on the nature of the breakage point. The analysis and mapping of the river breakages along the two rivers is done using high resolution satellite images combines with (limited) field verification. A snapshot from the latest status map from February 2022 is included below (SWALIM, 2022[12]).

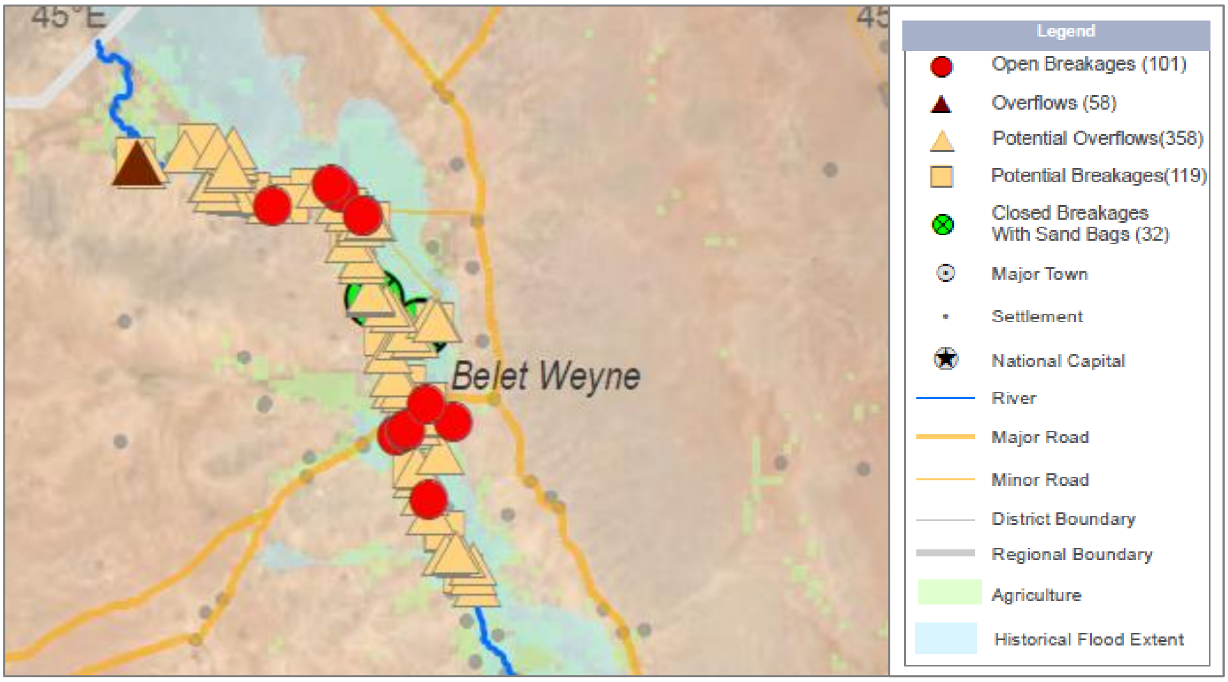


Figure 6.6 Snapshot of Shabelle River breakages and their status from February 2022 (Source: SWALIM).

As of February 2022, the reduced river flow and drought conditions have led to an increase of new river breakages. The study has identified 101 open points along the Shabelle, out of which 24 points

[12] SWALIM, 2022. https://faoswalim.org/content/status-river-breakages-along-juba-and-shabelle-rivers-somalia-%E2%80%93-february-2022

are new and the rest have remained open since the last survey in August 2021. Along the Juba River, 35 open points were identified out of which 5 are new points[13].

The underlying information on the nature of the breakage points can be particularly important in understanding where NbS has most potential – e.g. breakage points where flooding is caused by overflows (or points identified as potential overflows), prioritized for further investigation for bank stabilization through revegetation, reforestation or other NbS activities. See example snapshot below, noting open or potential overflows:

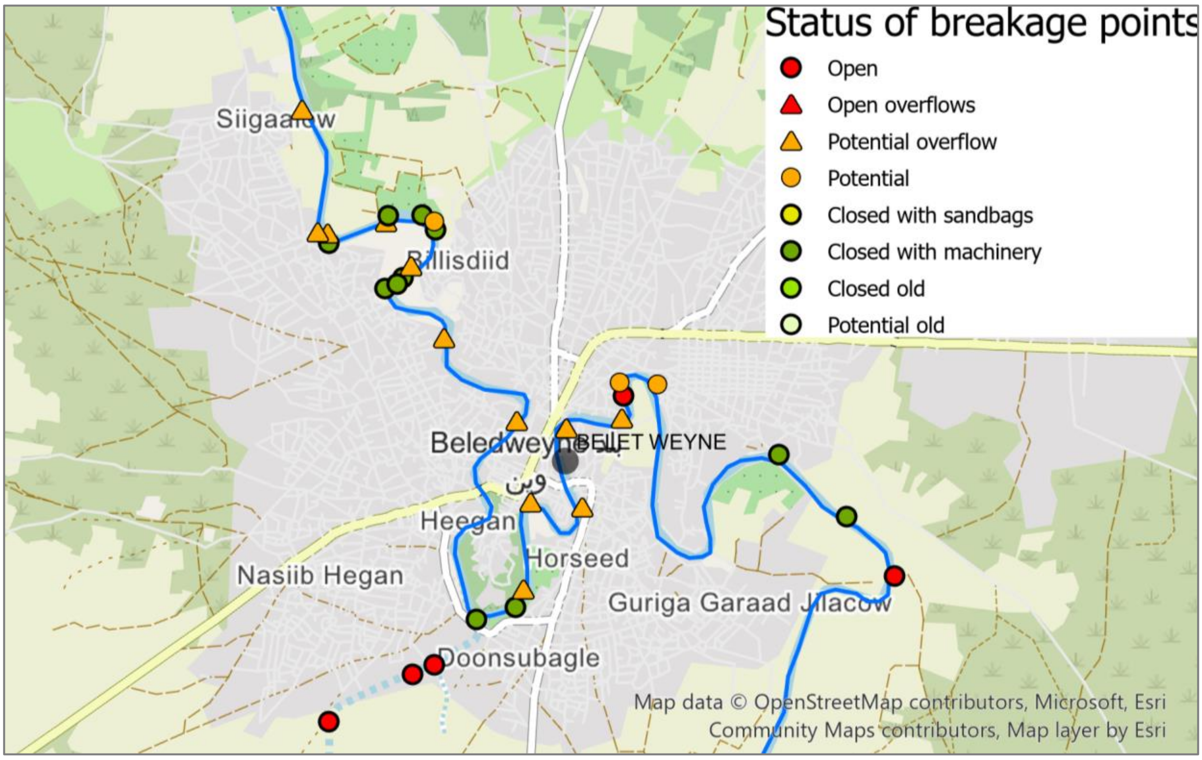


Figure 6.7 Embankment breakage sites around Beledweyne, data based on SWALIM shapefiles 2022.

Flash Flood Potential Indicators

Four different approaches to assess and map the potential for flash floods in Somalia have been investigated in this project: the Flash Flood Potential Index (FFPI), the Height Above Nearest Drainage point (HAND), the use of Global Precipitation Measurement (GPM) 30-minute GPM-Early data product, and the morphometric approach. It was not possible to draw conclusions on their applicability due to lack of data, however, these are available for analysis and download from the project online resource www.jubashabelle-tmo.org. for more information read the final report of the project on the findings of the flash flood research.

Once sites in need of flood hazard mitigation have been identified, the comparison of suitable NbS options and their prioritization should always take departure in assessing whether the NbS are technically feasible for the specific locations. The basin and country level datasets can help point to relevant locations for further investigation but given the highly localized nature of floods (especially flash floods), a technical site feasibility assessment would be required to derive precise indicator values for potential impact assessment and NbS comparison.

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[13] SWALIM, 2022. https://faoswalim.org/content/status-river-breakages-along-juba-and-shabelle-rivers-somalia-%E2%80%93-february-2022

6.2 Site Suitability and NbS Sustainability Assessment

Based on recorded NbS implementation experiences, including evaluation accounts of reasons for suboptimal performance of NbS, a selection of supplementary indicators is provided. These indicators address the broader picture of site suitability and NbS sustainability.

Additionally, the NbS option assessment and eventual prioritization can consider important co-benefits such as multipurpose use and new income generation activities from the ecosystem services. E.g., use of bank and soil stabilizing vegetation for grazing, fruit cultivation, etc. Assessment of the co-benefits can be particularly useful when comparing potential NbS interventions with conventional, 'grey' flood mitigation alternatives.

A selection of supplementary indicators to assess these aspects are included below. The list and selection should be amended to suit the specific NbS, given the solution diversity, and local setting.

Table 6.2 Indicators to inform planning of NbS for flood mitigation, Socioeconomics and Sustainability.

Socioeconomics		
Indicator	Explanation	Data
Number of beneficiaries reached by the NbS (population data)	Assessment of NbS reach in terms of beneficiaries. Population data can help assess the number of potential beneficiaries from the NbS interventions on a spatial scale.	Calculated as total amount of people benefitting from NbS. Alternatively, an estimate of % percentage of people in the target group that benefit from the NbS. Pop density maps available from AfriPOP and CIESIN, however resolution might be a challenge. A proxy of buildings could be used more successfully.
Clan distribution	Distribution of clans and clan boundaries informs cultural and social dynamics that may affect implementation and maintenance of NbS.	Somali clans in Somalia, Kenya, Ethiopia and Djibouti (A. Abikar, 1999). Available as a GIS layer.
Land tenure	Tenure rights and land uses surrounding potential NbS sites inform the governance arrangements required to ensure successful implementation and maintenance of NbS	No detailed spatial data are available, but the existing situation should be assessed on site basis using local knowledge and data sources.
Flood vulnerability indicators	Physical, social and economic vulnerability indicators for settlements in project focus areas have been estimated	Data are available as layers and a risk assessment tool can be used to interactively assign weights to estimate total vulnerability. See Final Report on flash floods research produced by the project.
Cost of implementation	Cost of implementation includes the necessary resources for assessment and implementation of the NbS.	Indicator is based on simple comparison of the estimated costs from lower to higher costs. Data to be sources from expert assessment, depending on NbS

Socioeconomics		
Indicator	**Explanation**	**Data**
		in question and its scale, drawing from previous country experiences.
Sustainability		
Conflict risk	Record of previous conflicts in the area (or present risk of conflict), e.g. number of conflicts within last 5 years within X distance from the potential NbS site.	- Armed Conflict Location & Event Data Project (ACLED) - Uppsala Conflict Data Program - Federal and state advisory and datasets
Local community involvement in the planning of NbS	Indicator helps to assess the extent to which citizens and other stakeholders are involved in the planning phase of the NbS project or initiative (qualitative, unitless)	Qualitative assessment, e.g. using a scale of 1-5.
Local community involvement in the implementation of NbS	Indicator measures the extent to which local community members and other stakeholders are involved in the implementation phase of the NbS project of initiative (qualitative, unitless).	Qualitative assessment, e.g. using a scale of 1-5.

6.2.1 Data for Supplementary Indicators

As most of the supplementary indicators assess socioeconomic and governance aspects, locally sourced data would always be preferrable to ensure the necessary level of detail and accuracy. Situation relating to aspects such as conflict and local governance structures may also change in time and with short notice. Site specific assessment is therefore recommended, including assessment of these qualitative indicators, whenever possible.

However, initial screening can be supported with some of the existing datasets that have either basin or national coverage. Where such are available, they are included below.

Number of beneficiaries

Population density data can help assess the number of potential beneficiaries from the NbS interventions on a spatial scale. When combined with flood risk or flood extent maps, this also informs of number of people at risk from flooding events.

District level population data are available in shapefile format from SWALIM's website for 2014, from the Population Estimation Survey (PESS) which gathered basic critical information on the Somalis living in urban, rural and nomadic areas (interviewed at water points during the peak of the long, dry season), and in settlements for internally displaced persons[14]. This data set can help estimating or prioritizing NbS beneficiaries on district level. See map example below, based on the datatset.

[14] https://spatial.faoswalim.org/layers/geonode:SOM_Population_PESS_2014#/

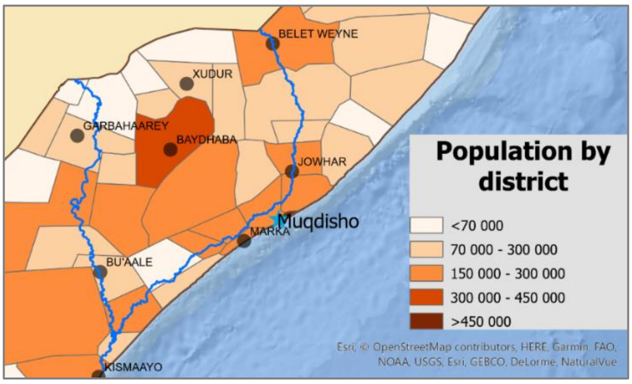

Figure 6.8 Population by district, sample area. Data from Population Estimation Survey (PESS), 2014. Downloaded from SWALIM.

Additionally, more detail could be gained if looking at number of households that will benefits from interventions (as opposed to district level population estimates). As part of the project, an exercise to digitalized data on dwellings was undertaken for selected target areas, which has the potential to offer much more spatial detail. These could be viewed in the context of e.g. how many dwellings/households are affected by flooding and from there deriving how many dwellings stand to benefits from flood protection measures through NbS. On a local level, the dwelling data also appear to give much more detail on the population concentration as opposed to district level data. E.g. see example zoom-in for Beledweyne below.

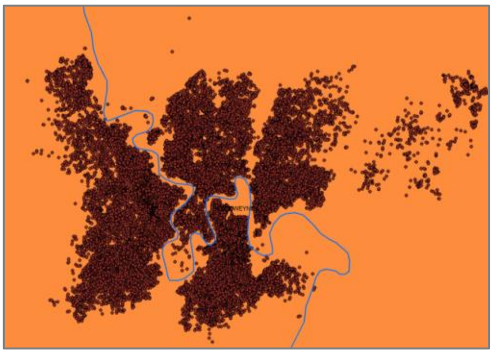

Figure 6.9 Dwellings in digitalized map format for Beledweyne. Source: OpenStreetMap.

High resolution gridded population data are available for Somalia from AfriPop project (2010)[15] as well as Center for International Earth Science Information Network - CIESIN - Columbia University (2018)[16]. The GPWv4 dataset provides estimates of population density for the years 2000, 2005, 2010, 2015, and 2020, based on counts consistent with national censuses and population registers. The resolution of data is 30 arc-seconds (approximately 1km). However, currently the resolution and data precision appear to be a challenge.

Land tenure

Land tenure can be a deciding factor in whether NbS can be successfully established. Land tenure impacts not only who owns the land on which potential NbS can be built, it also informs of the potential uses and user relationships of the land and its resources. E.g. private agricultural lands can

[15] Linard, C., Alegana, V.A., Noor, A.M. et al. A high resolution spatial population database of Somalia for disease risk mapping. Int J Health Geogr 9, 45 (2010).
[16] Center for International Earth Science Information Network - CIESIN - Columbia University. 2018. Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11

be used for cash activities such as growing certain crops, whereas lands that are not privately owned, can be equally vital for common uses by clan members for livelihood relevance – including grazing, wood collection, etc.

In Somalia, customary Xeer law addresses numerous aspects of land management with a focus on pastoral land use. This combines with more formal land deeds in some areas. Currently no spatial datasets were available for clear classification of these relationships, however it is recommended that these aspects are evaluated using expert and local knowledge when assessing feasibility and placement of NbS.

Flood Vulnerability Indicators

Based on available data, the following selection of indicators was produced by the research team:

- Physical vulnerability: disability, emergency safe place, emergency transport, distance to hospital, distance to police, distance to road, population density.
- Social vulnerability: literacy, education, employment status, schooling impact, health access, emergency plans, early warning.
- Economic vulnerability: income, credit access, property value, condition of dwelling, dwelling ownership.

Overall physical, social and economic vulnerability components are a product of the combination of their respective indicators. Our team has carried out a classification exercise for the purpose of illustrating the methodology and approach. This classification must be carried out by the stakeholders using their expert knowledge and when needed further data and supporting studies. This will be especially important for non-numerical indicators that are not susceptible of a direct classification using statistical methods such as quantiles for example.

The Risk Assessment application provides a tool for reclassification of vulnerability indicators and calculation of total vulnerability following the methodology described in this report. All data produced by this research study is available to be inspected and/or downloaded by the the National Flood and Drought Task Force members and members of state-level task force members.

Cost of implementation

Cost of implementation of the NbS presents an straightforward indicator (low to high cost) for comparison and prioritization of the potential interventions against other key indicators as their expected impacts on hazards reduction and the number of beneficiaries.

The breadth of NbS options means that it is not possible to predefine scale of low to high cost generally. The costs are connected to the scale (e.g. small riverbank focused reforestation and revegetation vs large scale restoration activities) and implementation modalities (e.g. implemented and co-financed by local communities or financed solely by government, administrations or development projects).

Nevertheless, it is recommended that cost is included in the framework to ensure cost efficiency of the interventions – e.g. most beneficiaries and/or most impacts on hazard mitigation for the investment.

Risk of conflict

Documentation from past NbS projects[17] has shown that NbS structures and project implementation have suffered from conflict presence in the areas. This has affected both implementation (safety) and maintenance of established NbS (limited access of staff and community members to NbS site due to safety concerns).

[17] See NbS catalogue document

In view of NbS sustainability, priority should therefore be given to locations experiencing low risk or occurrence of conflict.

For initial screening, datasets such as UCDP (Uppsala Conflict Data Program) can be used. The map below shows a record of registered conflicts in the 5-year period per district (latest available data are for years 2015 – 2019). The map could be updated with data from the latest years if such are available at district level.

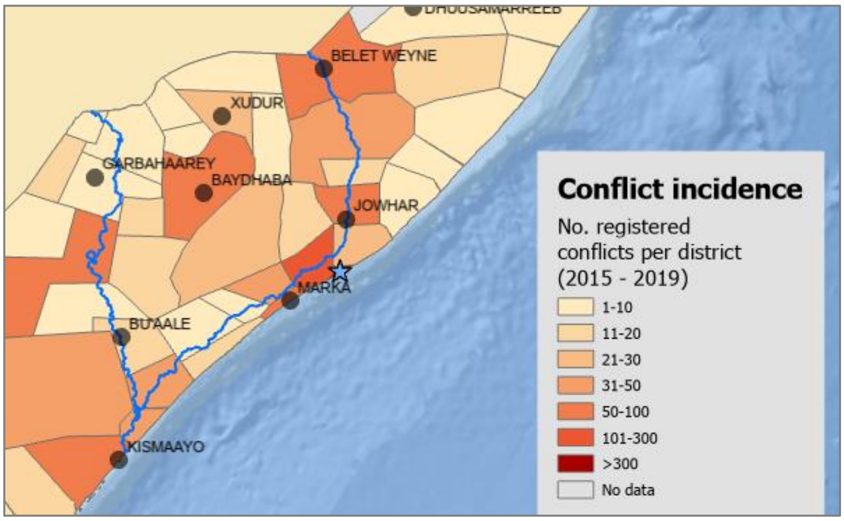

Figure 6.10 Number of conflicts per district (calculated based on registered conflicts in district for time period 2015 - 2019). Source: Uppsala Conflict Data Program, 2022.

Local community involvement in the implementation of NbS

Indicator measures the extent to which local community members and other stakeholders are involved in the implementation phase of the NbS project of initiative (qualitative, unitless)[18].

Similar to involvement in the planning phases, local community involvement in implementation of NbS can be beneficial for project sustainability. It creates ownership and ensures establishment of a common understanding of the project's longer-term maintenance or management requirements. In many cases, active involvement of local communities can be a precondition for NbS implementation and sustainability. For example, if NbS of revegetation and reforestation requires limiting of grazing activities for a limited period of time, acceptance and cooperation by users will be vital for success. In the same way, NbS project relying on land use change would require active involvement by local farmers or land users. Also, for constructed NbS structures such as sand dams and gabions, past experiences have shown that without lack of proper maintenance the structures risk rapid degradation.

As with the assessment of the community *involvement* in planning, a five-point Likert scale approach for stakeholder participation can be used to evaluate the extent (or estimated likelihood) of community participation in the implementation and maintenance of NbS, on a scale of 1 to 5 (No involvement to high involvement in implementation). The indicator can be amended to suit local needs (e.g., where level of uncertainty is higher, the scale could be simplified to e.g. 1-3)[19].

1. *Not at all:* No community involvement in implementation expected or possible

[18] Indicator is adapted from Wendling et al. 2019, Performance and Impact Monitoring of Nature-Based Solutions, European Commission, UNALAB: Urban Nature Labs.
[19] Scale is adapted to suit the NbS project focus.

2. *Inform and consult*: An essentially complete NbS project is presented to the community for information only, or in order to receive community feedback. The consultation process primarily seeks community acceptance of the NbS project at the implementation stage.
3. *Advise*: The project implementation is done by the task force of the NbS project team. Community stakeholders and key actors are invited to ask questions, provide feedback and give advice. Based on this input the project implementation plan may be altered.
4. *Partnership*: Community actors are invited by the task force, project managers or relevant authorities to participate in the implementation process. This could also be through creation of temporary or permanent job opportunities for community members. The local community is able to influence the implementation process.
5. *Community self-development*: The task force or project proponents empower communities and local stakeholder groups to manage the project implementation and evaluate the results. This could include e.g. setting up mechanisms for local maintenance and co-funding of the NbS structures that may enable long term sustainability of the interventions.

7 Recommendations

7.1 Nature-based Solutions Targeting Flash Flood Mitigation

Reforestation as a measure to mitigate the impacts of flash flood specifically did not prove to be effective. This is due to the limited areal coverage of the reforestation and the somewhat limited impact that the forest has on very heavy rainfall events, as it is mainly the initial millimetres of rainfall that are retained. Regarding terracing it is seen that the peak flow is reduced in both volume and maximum discharge. The reduction is not judged sufficient to justify terracing to this extent for flash flood mitigation only, but it could be seen as an added value if this is considered for agricultural purposes at suitable locations.

The analyses have shown that V-shaped weirs – and combined weirs having a smaller V-opening in the upper part of the dam – can reduce the peak flow of flash floods and thereby reduce downstream flooding. The structures will also increase local infiltration, and a clear trade-off is seen between flood peak reduction and infiltration. Data is not available, however, to design the structures or assess the efficiency of existing structures to provide general guidance on future construction.

It is recommended to test these structures at different locations in Somalia through the following activities:

1. Collect additional information on flash floods at several locations to enable assessment of the magnitude and characteristics of the local flood events, including their flashiness.
2. Model the potential impact of different structure types, as illustrated in this report, considering this information, and collect additional data on the topography at promising dam sites.
3. Select among these locations one or more sites where one or – preferably – several structures can be constructed, and the local population is willing to participate in their construction and maintenance.
4. Design and build the structures based on model results, local priorities on flood mitigation versus increased infiltration, and local expertise and experience.
5. Install monitoring of the water level upstream and downstream of the structures and collect data for at least two wet seasons, preferably longer.
6. Use the collected measurements to update the models and assess the performance
7. Prepare a design guide.

7.2 Nature-based Solutions Targeting Sediment

Based on the results from the three tested cases – namely: bank protection and stabilization efforts along the Shabelle in Somalia; reforestation/revegetation, implementation of sand dams, and gully protection of the Shabelle catchment in Somalia; and reforestation/revegetation of the Shabelle catchment in Ethiopia – a set of recommendations have been developed. It is recommended to:

1. Conduct further investigation into the implementation of NbS to reduce topsoil from the Somali catchment from entering the river, as this may reduce sediment deposition on the riverbed to a degree that also reduces flooding.
2. Further refine the 1D sediment transport model to better determine the relationship between the degree to which topsoil erosion is reduced in the Somali part of the catchment and the degree to

which flooding is reduced along the river (requires data collection as per recommendations in the following bullet points).

3. Select locations for NbS for bank stabilization based not on the sediment contribution to river flooding, but on other factors such as location of important infrastructure.
4. Collect grain size measurements of the suspended sediment and the riverbed at Beledweyne to confirm the model results.
5. Conduct a yearly river data collection campaign to measure cross sections and sediment information (grain size of suspended load and bed sediments and suspended sediment concentration) at a finer resolution along the length of the river.
6. Collect total suspended solids measurements at the four sampling locations (Beledweyne, Buloburde, Mahadey Weyne, and Jowhar) on a regular basis (quarterly or monthly).
7. Development of a long-term sampling plan to fulfil the data collection recommendations in the previous three bullets, including training for sampling techniques to ensure consistency across yearly sampling campaigns.

The established model has proven to be a useful tool for understanding some of the basic sediment-related mechanisms in the Shabelle River. As more data become available in future, the model can be updated further and with a higher confidence be applied for additional purposes, such as a tool for prioritization of interventions and for informing flood risk with higher accuracy.

A large-scale measuring programme will benefit river modelling and thereby lead to improved analysis and advice given. However, local piloting of some NbS can be done in parallel to continue data collection. The current model study has shown that collapsed banks do not significantly impact sediment-induced flooding on the site and elsewhere. Local pilot studies on improving irrigation intake channels can also be undertaken. It is, however, recommended that further investigation be conducted prior to pilot studies of NbS to reduce topsoil erosion so that the locations that are candidates for such pilots can be identified.

7.3 Prioritization for Upscaling

A framework of indicators is proposed to guide the National Flood and Drought Task Force when planning and prioritizing NbS interventions. Detailed recommendations per indicator are listed in sections 6.1.1 and 6.2.1. These indicators are also proposed to UNEP and the international community for inclusion in future development programming projects. The following general recommendations are presented:

1. A systematic approach to recording information in relation to NbS efficiency and impact is necessary to evaluate their true impact on flood and drought management. The available records are limited to assumptions on the benefits NbS will deliver, or contain accounts of impacts that are mostly based on anecdotal evidence. Only a handful of projects use data on recorded metrics of the impact based on comparison of the impact with the baseline.
2. Working very closely with local communities in developing, implementing and maintaining NbS as this is fundamental for success and sustainability.
3. Collecting information on key metrics in relation to e.g., discharge, volume of water stored, soil erosion rates, sediment deposition, discharge volume, velocity, is instrumental in measuring the individual project success, but also provides vital insights into the scope for upscaling NbS at basin and country scale.

4. NbS projects require a Monitoring and Evaluation (M&E) phase, with reporting included where the indicators provided in this report should be considered. It is recommended to consider the following:

   Recommended indicators for assessment of hazard mitigation potential: a selection of indicators that can assist assessment of the efficiency of NbS to mitigate flood hazards.

   Supplementary indicators to inform NbS sustainability: recommended indicators covering aspects relating to general site suitability, co-benefits, governance, and sustainability of the NbS that may inform long-term planning decisions.

   Where relevant, implement a gender-breakdown of the indicators.

Finally, MOEWR and the National Flood and Drought Task Force now have a catalogue where the successes and challenges of past projects are recorded. The catalogue provides a good framework against which future projects' M&E could report.

7.4 Available Datasets and Next Steps

The research outputs, namely, all data collected, and all data generated including model results, have been delivered to the MOEWR and the key datasets with the main findings (including project reports) have been uploaded to the portal for dissemination.

The conclusions and recommendations of this work have been discussed with the MOEWR and the National Flood and Drought Task Force in the final workshop held on the 28th of March 2022. The Ministry laid out an outlook for the future based on the recommendations. In the short term, the following needed actions were highlighted:

- Further data collection, field work, to improve the developed models and refine/improve risk reduction actions.
- Disseminate data collection recommendations of the research work, so that other projects that are ongoing in the field, can incorporate this into their workplans if possible.
- Targeted capacity building activities to support operation, transfer and maintenance of the tools developed under the FCDO project.
- More in-depth assessment of existing capacity and needs. Thematic areas identified during the current project include river hydraulics, sediment transport, water resources scenarios, and data management.
- Elaboration of a monitoring network for water flow and sediments: basic/best version depending on funding and accessibility/security at sites. The recommendations of the research work regarding top priority parameters to be collected should be followed.
- Institutional support to MOERW/National Task Force such as field visits, meetings, IT equipment, study tour, amongst others.

In the medium term:

- Selection of test sites for NbS option(s) – detailed monitoring is required to document costs/impacts and to develop proto-concept(s) – should be carried out in collaboration with NGOs already active in the respective locations and involved in risk reduction.
- Integration and streamlining of the proposed indicator framework into MOEWR project evaluation and monitoring processes (look to apply it already to any ongoing projects involving NbS implementation)

- Transboundary Water Allocation model for the entire Juba-Shabelle River System. As a point of departure, MOEWR is guiding a transboundary water resources study with UNEP support from March to May 2022. The study is a follow up activity of the FCDO supported research.
- Support to transboundary dialogue with Ethiopia in order to pave the way for the setting up of a transboundary institutional mechanism for cooperation.
- Support to establish joint monitoring program and transboundary data sharing protocols.

Finally, it is recommended that for sustainable application of this project's outcomes, the next step in the collaboration between MOEWR and UNEP is aimed at strengthening the capacity of the federal and state-level authorities. Via the project's workshop programme, requests by MOEWR and task force members have been put forward and relevant areas for development identified. Collaboration towards the development of a concept note is underway.

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