IWRM Programme Rwanda

TR26 – Volcanoes area flood management

January 2017



Kingdom of the Netherlands

Issue and revision record

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Water for Growth Rwanda is a platform to promote improved management of Rwanda's water resources. A joint Rwanda-Netherlands initiative, Water for Growth is supported by the IWRM Programme Rwanda, implemented by Euroconsult Mott MacDonald (lead partner) in association with SNV and SHER. www.water.rw

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Content

Annexes

Tables

Figures

List of Abbreviations

CCPA	Climate Change Programme of Action
DDG	Deputy Director General
DG	Director General
EDCL	Energy Development Corporation Ltd
EDPRS-2	Economic Development Poverty Reduction Strategy - 2
EKN	EKN Embassy of the Kingdom of the Netherlands (in Rwanda).
EMM	Euroconsult Mott MacDonald b.v.
EIP	Early Implementation Project
EUCL	Energy Utility Cooperation Ltd
EWSA	Energy, Water and Sanitation Authority
GIS	Geographical Information System
GoR	Government of Rwanda
GWP	Global Water Partnership
Ha	Hectare
ICT	Information Communication Technology
ISU	Integrated Water Resources Management Support Unit
IWRM	Integrated Water Resources Management
IWRMD	Integrated Water Resources Management Department
KIST	Kigali Institute of Science and Technology
km	Kilometre
M&E	Monitoring and Evaluation
MIDIMAR	Ministry of Disaster Management and Refugee Affairs
MIGEPROF	Ministry of Family and Gender Promotion
MINAFFET	Ministry of Foreign Affairs and Cooperation
MINAGRI	Ministry of Agriculture and Animal Resources
MINALOC	Ministry of Local Government
MINBUZA	Ministry of Foreign Affairs (Netherlands)
MINECOFIN	Ministry of Finance and economic Planning
MINEDUC	Ministry of Education
MINICOM	Ministry of Commerce
MININFRA	Ministry of Infrastructure
MINIRENA	Ministry of Natural Resources
MINISANTE	Ministry of Health
MIS	Management Information System
mm	Millimetre
MoU	Memorandum of Understanding
NCEA	Netherlands Commission for Environmental Assessment
NGO	Non-governmental organization
NWCC	National Water Consultative Commission
NWRMP	National Water Resources Master Plan
O&M	Operation and Maintenance
PoA	Programme of Actions
PSC	Programme Steering Committee
RAB	Rwanda Agriculture Board

RBS	Rwanda Bureau of Standards
RDB	Rwanda Development Board
REMA	Rwanda Environment Management Authority
RMA	Rwanda Meteorological Agency
RNRA	Rwanda Natural Resources Authority
RURA	Rwanda Utilities Regulatory Authority
RWP	Rwanda Water Partnership
SDG	Sustainable Development Goals
SEA	Strategic Environmental Assessment
SHER	SHER Ingénieurs Conseils s.a. - Société pour l'Hydraulique l'Environnement et la Réhabilitation
SNV	Stichting Nederlands Vrijwilligers
WATSAN	Water and Sanitation
TA	Technical Assistance
WASAC	Water and Sanitation Corporation (formerly Energy, Water and Sanitation Authority)
WIC	Water Inter-ministerial Committee
YWP	Young Water Professionals

Executive summary

Introduction

Heavy rainfall in the volcanoes area often results in floods. Whereas the observed floods may appear similar in nature, the dynamics of floods in the volcanoes area are quite different according to their locations: classic torrential rivers in the Musanze urban area and Sebeya catchment, flooded endorheic areas (catchments without external outlet) in Byangabo sector, and flooded “dry thalwegs” north east of Rubavu disctrict.

A study was implemented by “Water for Growth Rwanda”. This memo provides the final results. The main studied rivers are the following ones (see Figure 1):

- Musanze-city sector: Rivers Rwebeya, Muhe and Susa
- Byangabo plateau sector: Rivers Murufurwe, Mutobo, Kinoni, Bikwi, Rungu and Nyabitondore.
- Sebeya Catchment: Rivers Sebeya, Karambo and Pfunda

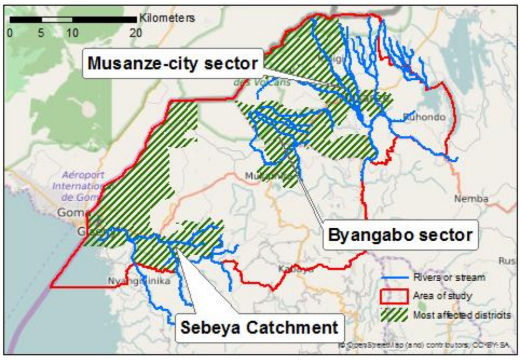


Figure 1 Location of the study area

Recommended interventions

An overview of recommended urgent interventions linked to key action holders is listed in Table 1 below. A prioritisation of actions is provided in the Technical Summary, and in the main report.

Table 1: Recommendations for urgent interventions

Intervention / responsible agencies	RNRA	MIDIMAR	District of Musanze	Distric of Rubavu	District of Nyabihu	MININFRA / RTDA
Bridge on river Muhe (RN2 road): erosion around the corrugated metal pipe severely threatens the bank supporting the road. Earlier recommendations to RTDA for repair have not been implemented. Concrete injections need be made urgently (preferably before 20th of September 2016) to stop the phenomenon. The twisted part of the pipe (at the entrance) is to be replaced or fixed. The pit between the weir and pipe entrance is to be filled with concrete (scoured ground at this place has led to the pipe damaging).						done
New brige on river Pfunda: population is worried about the flood that maybe caused by Pfunda river due to the new road under construction that might form a barrier for the water in the valley. The RNRA and international experts confirm the risk. Worries exist that the free space under the bridge crossing the river will not be large enough. A check on hydraulic studies made seems needed.				X		X
Mugogo, Murufurwe and Kinoni lowlands: o Unblocking caves that used to evacuate water; o Encourage inhabitants in the area to continue building check dams on small streams heading to caves to avoid obstruction.	X					
Anticipate further incoming sediments: river dredging needs to be scheduled regularly on Rwebeya River (from confluence with river Muhe to downstream of the main road's bridge).			X			
Erosion issues: warn house owners located less than 10 meters from the edge of a steep embankment that threat is real and that they need to be alert for flood warnings.		X	X			
Appoint two "flood watchers" on Rwebeya and Muhe rivers to warn authorities in case of an important flooding event in a formalized way. Watchers should be ideally located in Kinigi (Muhe) and nearby the cycling center (Rwebeya).	X	X	X			
Appoint two "flood watchers" on river Karambo (living at the end of the steep-sided part of the river), to warn authorities in case of an important flooding event.	X	X		X		
Appoint two "flood watchers" for each river Kinoni and Murufurwe (living upstream, at the end of the steep-sided part of the river) to warn authorities in case of an important flooding event.	X	X	X		X	

Good and poor examples of issues identified during the field survey

Figure 2 Example of efficient maintenance works on river Rwebeya (Bridge on RN2 road from Musanze to Kinigi)

Figure 3 New bridge on river Pfunda: former bridge has not been destroyed, potentially hampering peak flows

Figure 4 Muhe river bridge (view from upstream): corrugated metal pipe severely damaged (repaired in meantime)

Location of the main issues

In figures 5, 6 and 7 the following features are shown:

- the red lines represent the main roads;
- the blue polygons draw the estimated flood-prone area (not definitive because ongoing study).

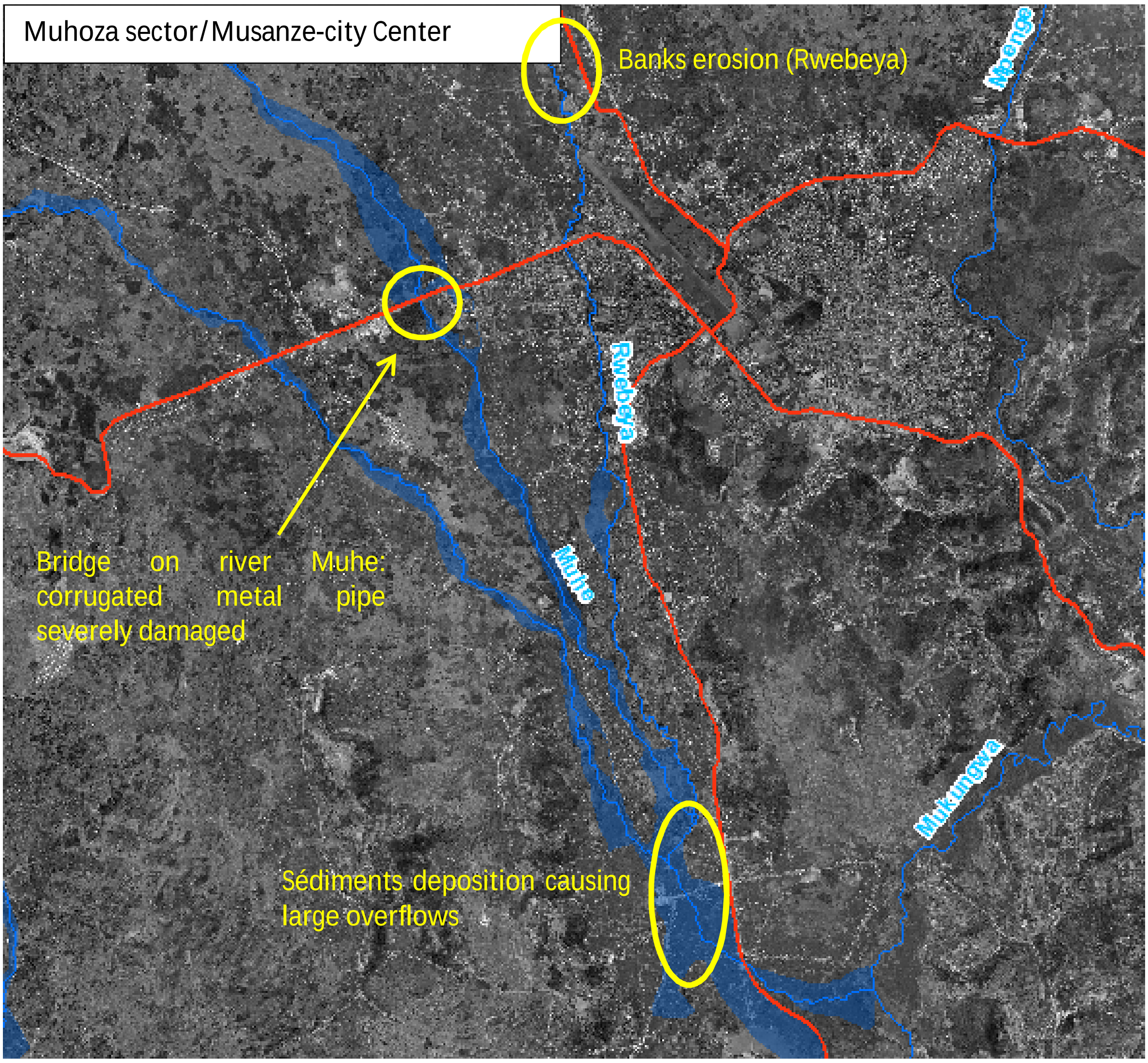


Figure 5: Musanze-city Center flood risk map. Status: Draft
Based on: modeling + testimonies of local residents

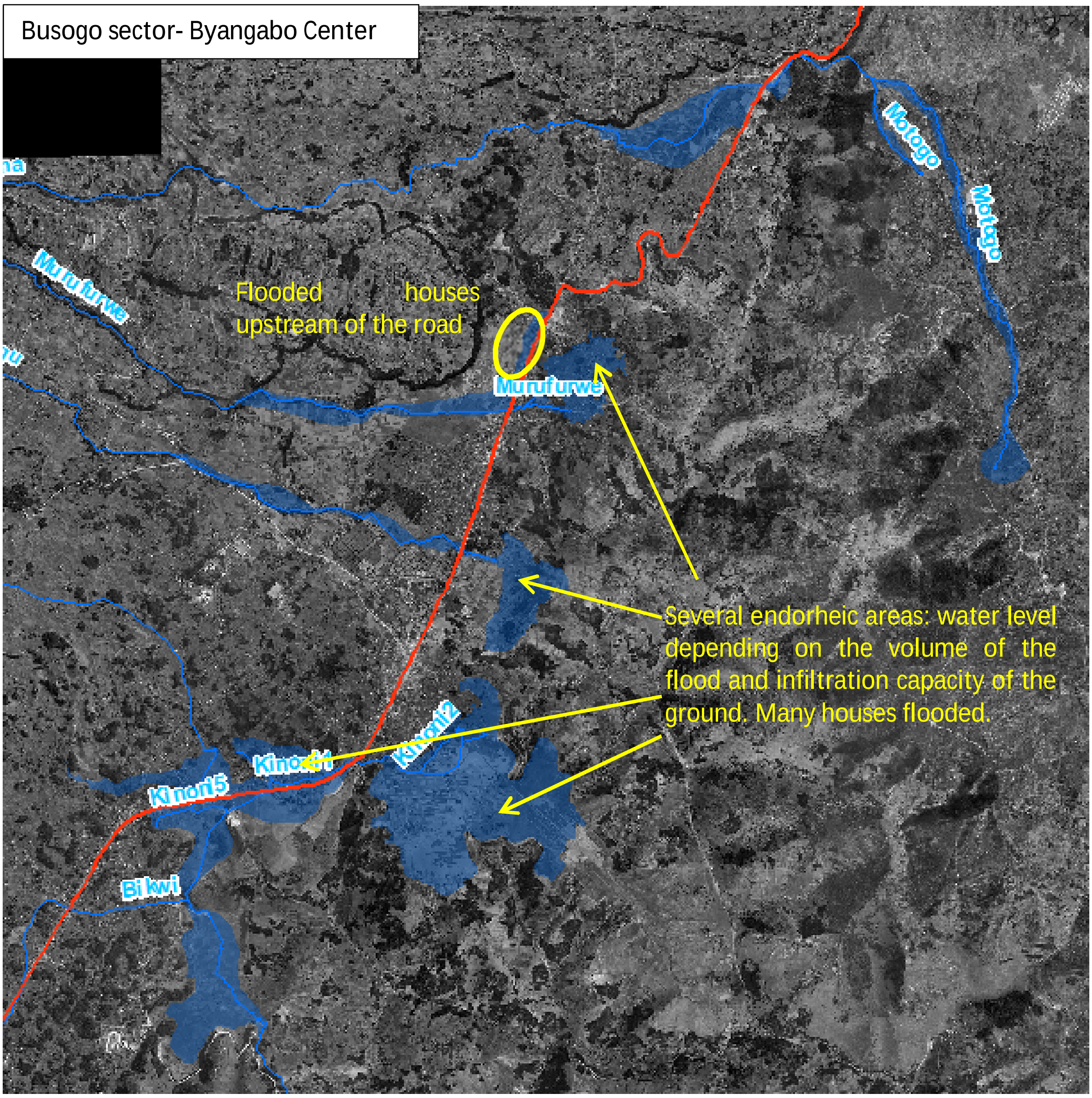


Figure 6: Byangabo Center flood risk map. Status: Draft
Based on: testimonies of local residents

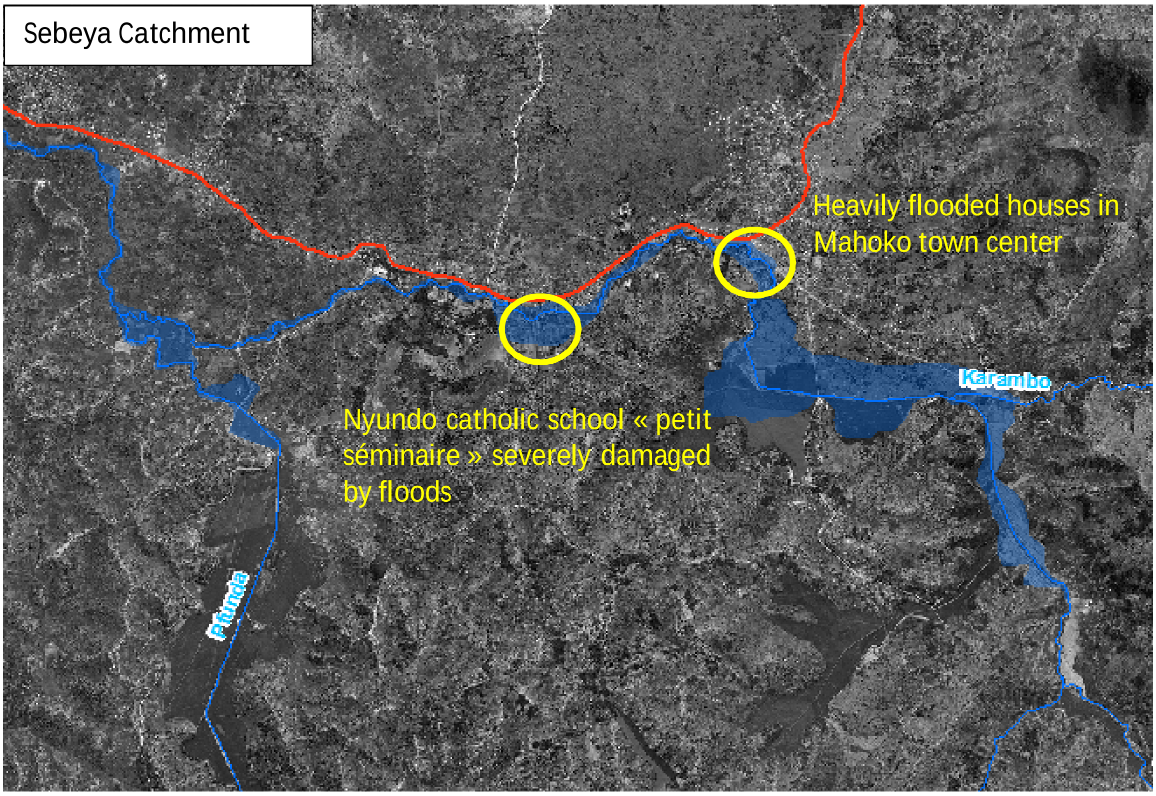


Figure 7: Sebeya flood risk map. Status: Draft
Based on: testimonies of local residents / Geomorphology of the catchment

Technical summary

The present report follows the Inception Report handed in at the end of the first mission (15th – 30th may 2016) which presented the study area and the methodology to be considered.

The current report incorporates the results of the second mission (16th Aug – 14th Sept) and the third (24th Oct – 9th Nov) and includes:

- Site visits minutes (all the study area);
- Hydrological study;
- Hydraulic study;
- Floodrisk maps;
- Mitigation works.

The main results are provided in the sections below.

FIELD VISITS

Field visits have been performed in May, August and September. They have produced an amount of important information, mainly about:

- Rivers characteristics
- Problems of flooding
- Frequencies of flood
- Structures' problems

For North-East rivers:

- Rwebeya River
  - Upstream of Musanze, the river bed is very deep (~10m); some canyons have even been dug into the bedrock. There is no overflowing.
  - In the crossing of Musanze's urban area, river training has been gradually made since a dozen of years. There is no overflowing, due to these works.
  - Downstream of Musanze, the river bed becomes globally smaller with an insufficient capacity that triggers overflows for frequent flooding events.
  - Upstream of Musanze, the main issue is erosion: the important depth of the river bed generates high slopes embankments which are unstable when a flood occurs. Many houses are threatened; some of them have been destroyed.
  - Another issue is the sediment transport. Deposition areas have been seen. Some areas have been extracted.
- Muhe River
  - Overflows occur almost everywhere on Muhe River.
  - Erosion appears not to be a major problem on this river.
- Susa River
  - Overflows occur almost everywhere on River Susa due to the lack of capacity of the channel. Indeed, the presence of hard basalt layer under 70 cm of erodible topsoil prevents the river from naturally digging a channel.

- Sediment deposition is an important issue on the river, especially in the downstream part (Muko neighbourhood). Most of the sediments are brought by rivers Rwebeya and Muhe. The bed level rises after each important flood and river and bridges capacities are reduced.

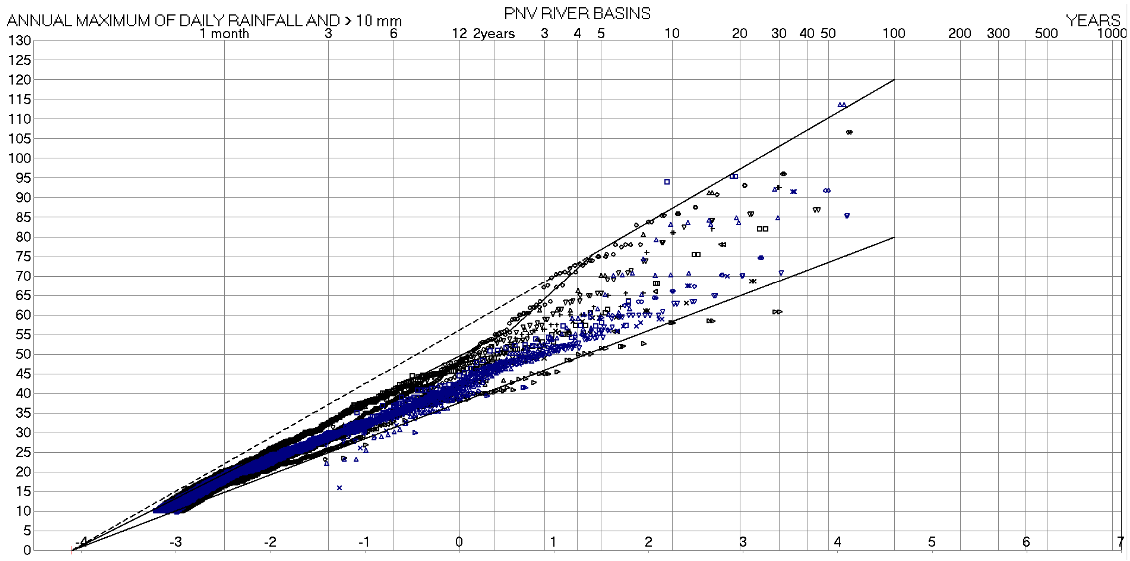
- Mudakama / Mutobo River
  - Downstream the drinking water plant, there are a lot of overflowing places.
  - At its extremity, Mutobo River separates into two branches. Both of the reaches of the river end into caves
- Endorheic Rivers: Murufurwe, Rungu, Kinoni & Nyabitondore, Bikwi
  - These rivers are all endorheic that means they have no exit that is no confluence with other river or lake. Their water is progressively infiltrated in the volcanic ground. At their extremities, they are diverted to different caves which absorb more or less all the discharge.
  - In case of extreme flood as it occurred in May 2016, the lowlands nearby the caves are flooded.
  - The elevation of the road RN2 forms dike upstream of which there is flooding due to the lack of capacity of the culvert. These flooding areas permit to reduce discharge downstream.
  - Erosion phenomena are a minor issue on this sector.
  - Sediment transport has been witnessed, under bed load and suspended load.

For South-East rivers:

- Sebeya catchment
  - The Sebeya catchment consists of four main rivers: Sebeya, Pfunda, Karimbo and Bihongoro. The last one has not been surveyed due to impossible access (no passable track).
  - Geology of catchment area consists in granite.
  - The main issue that concerns Sebeya catchment are overflows.
  - But sediment transport is also an important issue on Sebeya River and is mainly caused by mining activities in the upper catchment, official as well as clandestine.
- Thalwegs North-East of Gisenyi
  - The area consisting in the sectors of Cyanyarwe, Rubavu, Bugushi and Busamana has no rivers reported in the official GIS data. Watersheds have been generated automatically to locate potential floodplains. In fact there is no visible channel on aerial photographs. The morphology is sometimes similar to an alluvial fan: water can flow indifferently into several directions.
  - These thalwegs carry water twice a year, during the autumn and spring seasons. The floods dynamic is very particular on this area due to the strong permeability of the soils: when a storm (local rainfalls) strikes somewhere on a catchment area, flood propagates downstream on few kilometres before it disappears due to high seepage.

ANALYSIS OF EXTREME RAINFALL

Fourteen rain-gauges have been analysed. Annual maxima of daily rainfall (Rd) and values over threshold have been used. The SPEED method, developed and applied by ARTELIA since more than 20 years, has been used side by side with the curve number method from the USA. The SPEED method offers a means of significantly reducing the sampling uncertainty on the determination of rainfall in comparison with conventional statistical methods that adjust the statistical laws to the local values from a rain gauge. It is thanks to considering that all fit lines have a same origin. The results show that Rd100 is between 80mm and 120 mm and Rd10, between 60mm and 90 mm.



HYDROLOGICAL STUDY OF NORTH-EASTERN VOLCANIC BASINS

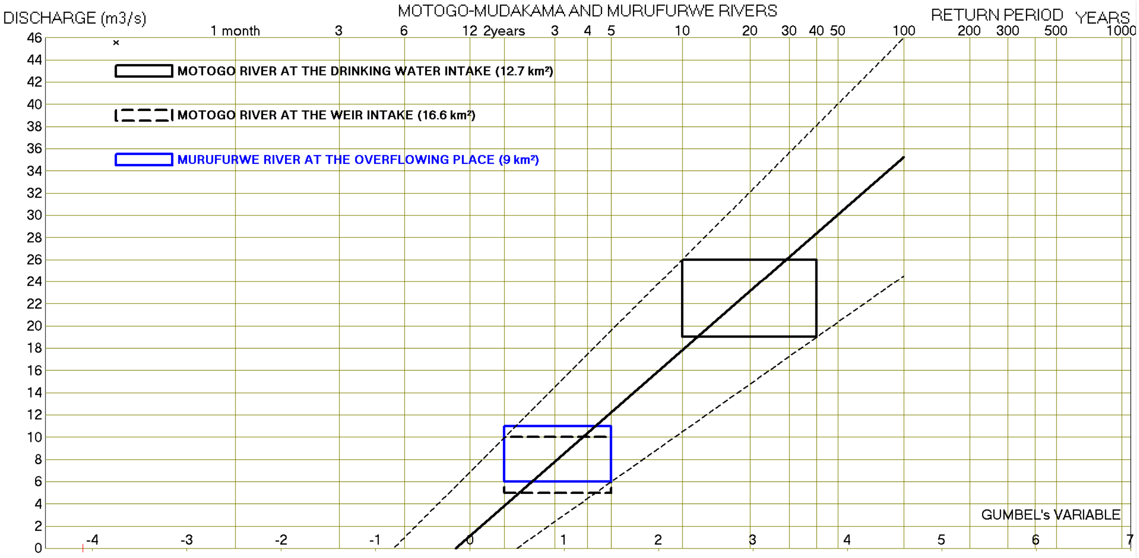
Analyses of previous existing reports and rainfall data have shown that:

- The precipitations are of stormy type, due to the rise of the masses of wet air which condense at high altitude.
- These phenomena concern at the same time only a surface of in most 50 km² to 100 km² (in fact probably less, according to testimonies – 30 km²).
- That is why, very often, floods occur in places where it has not been raining, the rain being in the upper catchment.

Due to this and to the fact that there are no data related to discharges on the small river basins of the north part of the study area, statistic methods and deterministic methods are not opportune. A probabilistic method is preferred in such situations, and was applied in this study.

Lacking proper records in the water resources information systems, information was collected during field surveys. For each event we computed discharge and the estimated return period, matched by an interval of uncertainty.

The uncertainty rectangles have been reported on graphs and statistic lines have been fitted as shown on the following figure.

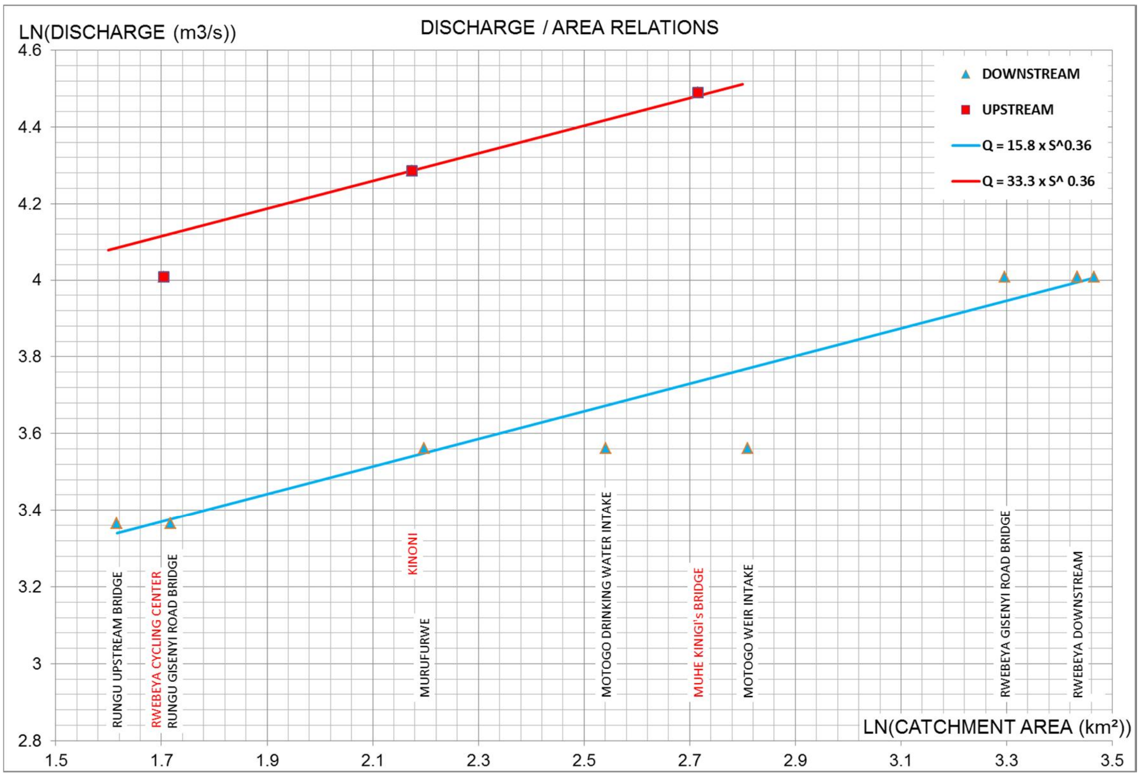


Analysis of all results leads to find that discharges vary versus catchment area with the following relation:

$$Q_T = A_T \times S^{0.36}$$

The 0.36 value is due to the fact that (heavy) rainfall, typically of very local nature, usually does not cover the whole catchment upstream of the point of observation.

We have also observed that A coefficient decreases from upstream (before overflowing) and downstream (after overflowing and infiltration in the ground of a part of the water). Results are as follows :



HYDROLOGICAL STUDY OF SEBEYA RIVER BASIN

On this catchment three different methods have been used in order to use existing data and to compare the results:

- The first method is the probabilistic method used for the North-Eastern volcanic basins.
- The second one exploits the data of height available at the river gauge of Nyundo. Rating curves have been established thanks to gauges and hydraulic modelling. The samples of discharges obtained have been analysed with a Gumbel law.
- The third method consists in using hydrologic model and two extreme hypothesis about 100y daily rainfall, storm area expansion and soil type (CN method).

A comparison of results is as follows.

Table 2: Comparison of methods to assess peak discharges (T=100)

Location	S.BV (km²)	Probabilistic method	Statistic method	Hydrological model
Sebeya at Nyundo sector	~ 210	72 [60 - 85]	70 [56 - 82]	[40 - 155]
Sebeya downstream Pfunda River	360	103 [89 - 116]	-	-

Calculated 100 year return period values thanks to CN method vary from 40 to 155 m^3/s. The probabilistic value of 72 m^3/s is contained into this interval, and also within the maximum interval found previously with probabilistic and statistic methods [60 m^3/s – 82 m^3/s].

Therefore, a hydrological model cannot predict exactly what happens on a catchment. This also highlights the fact that a field survey is essential to estimate the real occurred events and criticize the data coming from the gauging station (which were wrong due to an erratic rating curve).

HYDRAULIC STUDY

Hydraulic models have been built on almost each river with HEC-RAS software and for different purposes:

- To calculate a range of discharge for a flooding on local parts of the river where high water marks have been recorded;
- On longer river sections, to check the capacity of the channel. For example, on Rwebeya River, the urban part of the river has been modelled to check if any overflow occur for 100y return period;
- On the endorheic rivers, to estimate the distribution of the flood volumes between different storage areas;
- To estimate flood damping (e.g. Sebeya & Pfunda rivers);
- To map the flood prone area.

MAPS OF FLOOD PRONE AREAS

Mapping has been performed using two methods :

- Modelling;
- Expert judgement.

MITIGATION WORKS

The work has consisted in giving technical solutions. Feasibility study and detailed design must be led by local authorities (IWRMD, MINIMAR, District), later on, taking into account all local aspects.

The following proposed works mainly consists in lateral protections against erosion, hydraulic structure resizing, river training, river diversion and very local containment. Some of the measures are catchment-scaled and require to be implemented widely to be efficient.

ID	River	Type	Comment	Proposed priority
1	Rwebeya	Bank protections	Lateral gabion protections to prevent banks collapsing	2
2	Rwebeya	Bridge fixing	Gabion weir to be built downstream on main road's bridge	1
3	Rwebeya	Deposition area	River bed enlargement for sediment deposition	2
4	Susa	River training	Enlarging the capacity of Susa river upstream of the main road and reconstruction of existing structures.	2
5	Susa & Muhe	Bridge reconstruction	Reconstruction of bridge under Gisenyi road (larger structure)	1/2
6	Mutobo	Levee	Levee to be constructed right bank along Wasac plant	3
7	Murufurwe	Embankment	Reconstruct houses to road's level (rising ground)	3
8	Rungu	Levee	Levee to be built right bank to protect the university	3
9	Sebeya	Diversion channel	Mahoko diversion channel to be built	2
10	Sebeya	River training	River training near "Petit séminaire", Nyundo	2
11	Karambo / Gisunyu	Bridge fixing	Strengthening Gisunyu's gully damaged bridge	1
12	Whole area		Locate news appearance of new gullies and act appropriately	1
13	Whole area		Encourage new agricultural practices aiming at soil conservation	2
14	Whole area		Early warning systems	3
15	Whole area	Water storage		NA
16	Whole area	Reducing water velocity		NA

1. Introduction

1.1 Hydrological system of Rwanda

The hydrological system of Rwanda is sub-divided into two major basins (Nile basin covering 67% of the country's territory and Congo basin covering 33%) and nine level one catchments as illustrated in the following map.

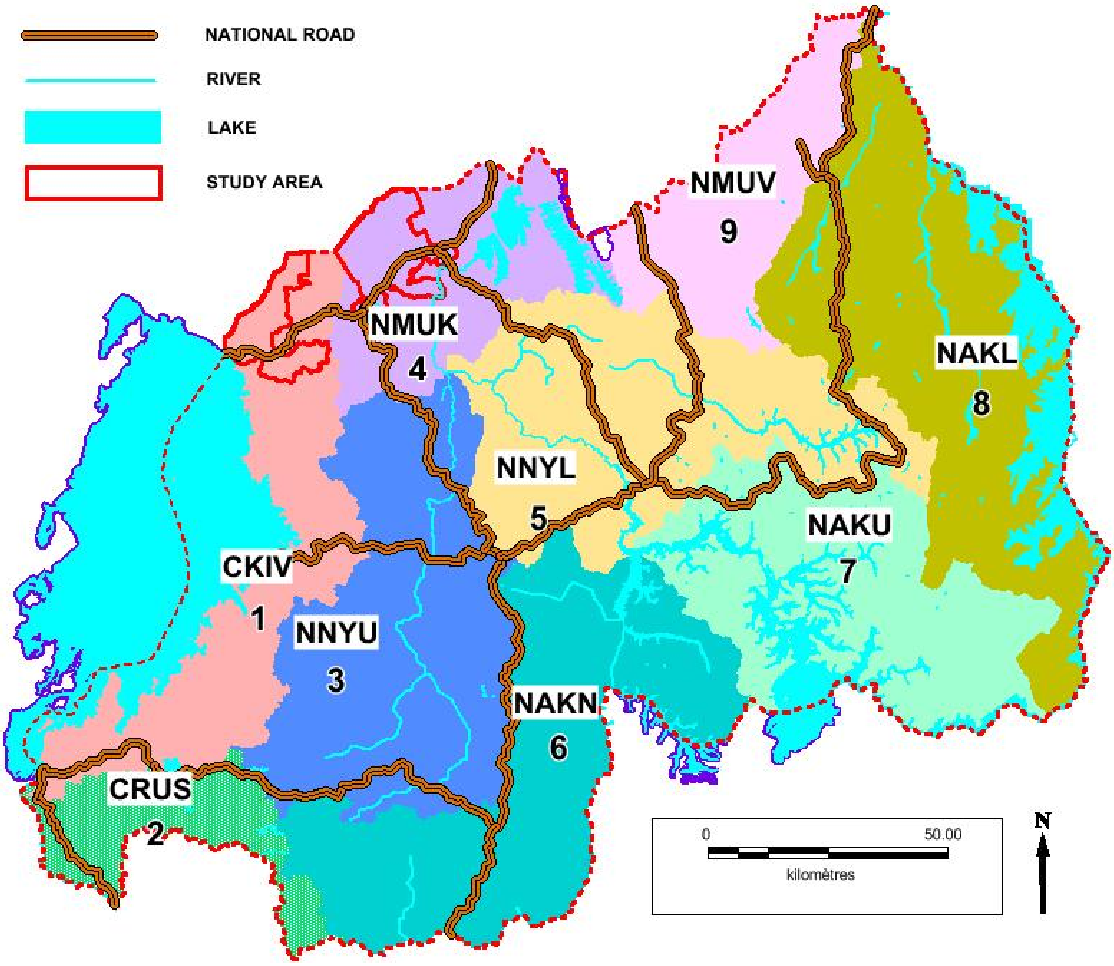


Figure 8: Hydrological catchment of Rwanda

In the above map, the initials:

1. CKIV stands for Congo Kivu catchment
2. CRUS stands for Congo Rusizi catchment
3. NNYU stands for Nile Nyabarongo upper catchment
4. NMUK stands for Nile Mukungwa catchment
5. NNYL stands for Nile Nyabarongo lower catchment
6. NAKN stands for Nile Akanyaru catchment
7. NAKU stands for Akagera upper catchment

8. NAKL stands for Akagera lower catchment
9. NMUV stands for Nile Mvumba catchment

1.2 Special IWRM study : Flood management volcanoes area

In line with the Rwanda National Policy for water resources management and its strategic implementation plan, the Government of Rwanda wants to rehabilitate the entire Mukungwa catchment (4), which has a total area of 1,902 km², of which 119 km² are covered by the Volcanoes National Park.

In this connection, the Ministry of Natural Resources through the Rwanda Natural Resources Authority intends to carry out, with support of the IWRM Programme, an assessment within the catchments in the volcanic area to identify the areas contributing the most to flood production and propose the mitigation measures and activities to be carried out in the catchments, so that the rehabilitation efforts can start from there and cover the entire lava region progressively.

1.3 Introduction to the present study

The purpose of the study is to contribute to reduction of flood risks and mitigation of impacts of flooding in the most affected downstream areas in the lava region.

The main objective of the study is to come up with a concise integrated plan for flood risk management in the area. The plan may include upstream measures to reduce or delay discharges, hydrological measures at key bottlenecks to allow for easier conveyance of water to reduce local flooding (e.g. at intersections with roads), and downstream measures to reduce impacts, such as zoning plans for land use and habitation.

Finally, the results of this report need will be used to reduce risks for families and businesses from flood.

The most affected sectors are Kinigi, Muhoza, Musanze, Kimonyi, Nkotsi, Gataraga and Busogo of Musanze District, as well as Mukamira Sector of Nyabihu District, and the northern sectors in Rubavu District.

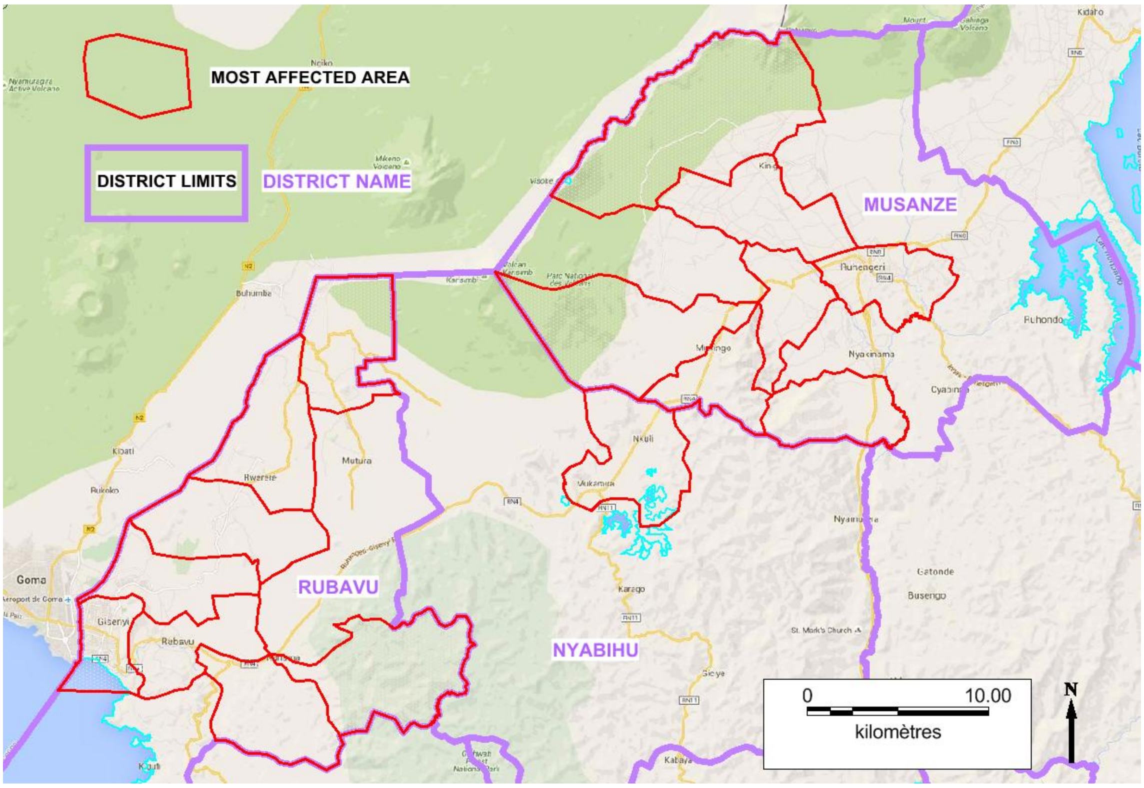


Figure 9: Map of most affected sectors

Terms of reference (TOR) are exposed in appendix 1.

After a first mission, in May 2016, TOR have been adjusted as they are exposed in appendix 2.

Mainly, this scope of work covers:

- Develop flood maps (flood prone area, flood extent, depth) based on a T=100 return period;
- Proposal flood management plan.

1.4 General description of the studied area

1.4.1 Topography

Topography has been first analysed thanks to SRTM 30m (Shuttle Radar Topography Mission – size of cells = 30m). The following map present results obtained.

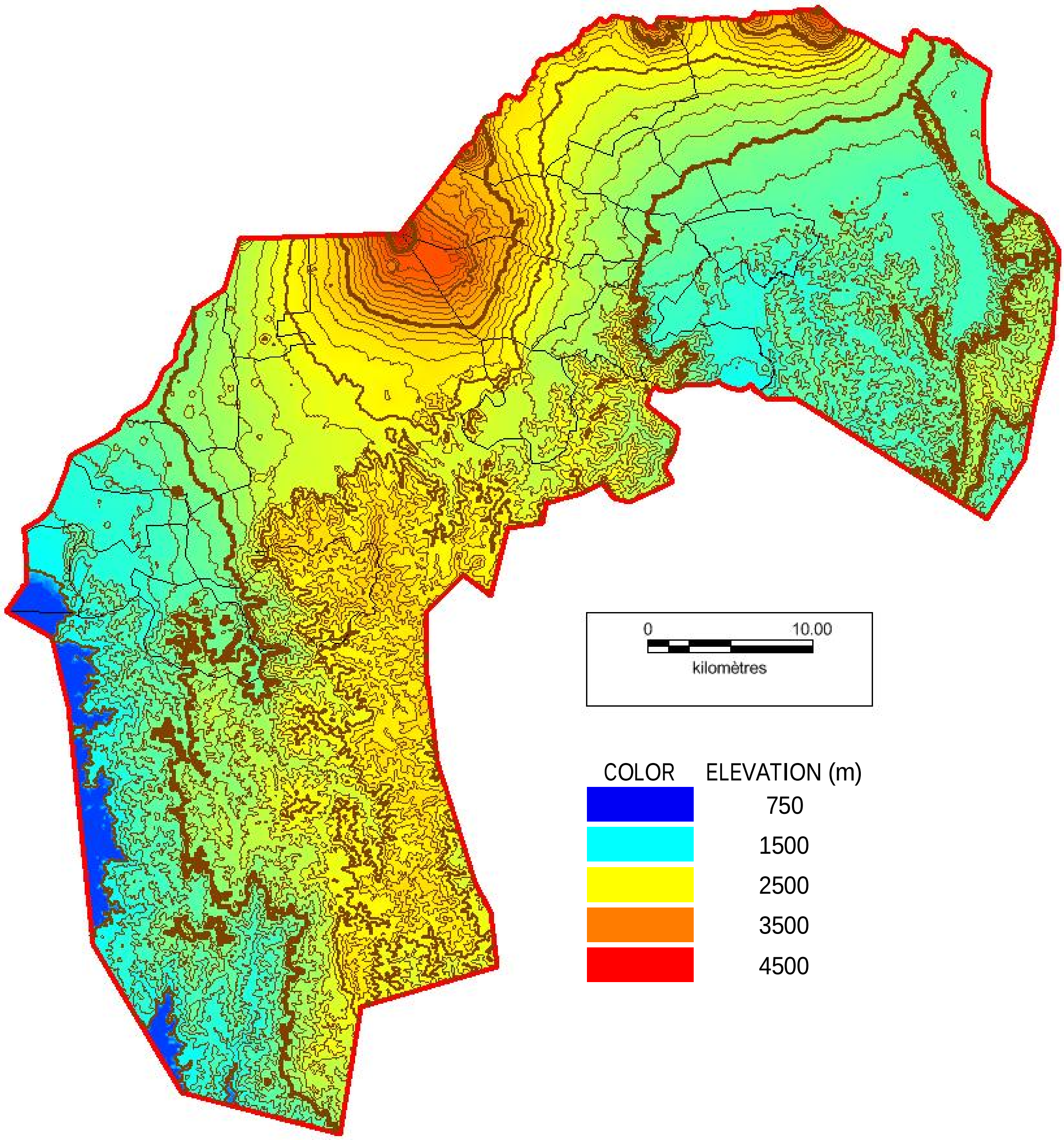


Figure 10: Elevation map

Elevations of the catchments are between 1400 m and 4000 m.

DEM 10m is also available and has been used for more detailed analyses.

1.4.2 Hydrography

A shape file (GIS file) of the rivers has been given by IWRM (Resulting from the analysis of the ortho-photographies of 2010).
We have also drawn the axes of the depressions thanks to STRM 30 and DEM 10, using a GIS and we have compared the results with the existing shape file.
Differences have been studied with aerial-photographies obtained with Google Earth and with field investigations.
The results are shown on the following figure.

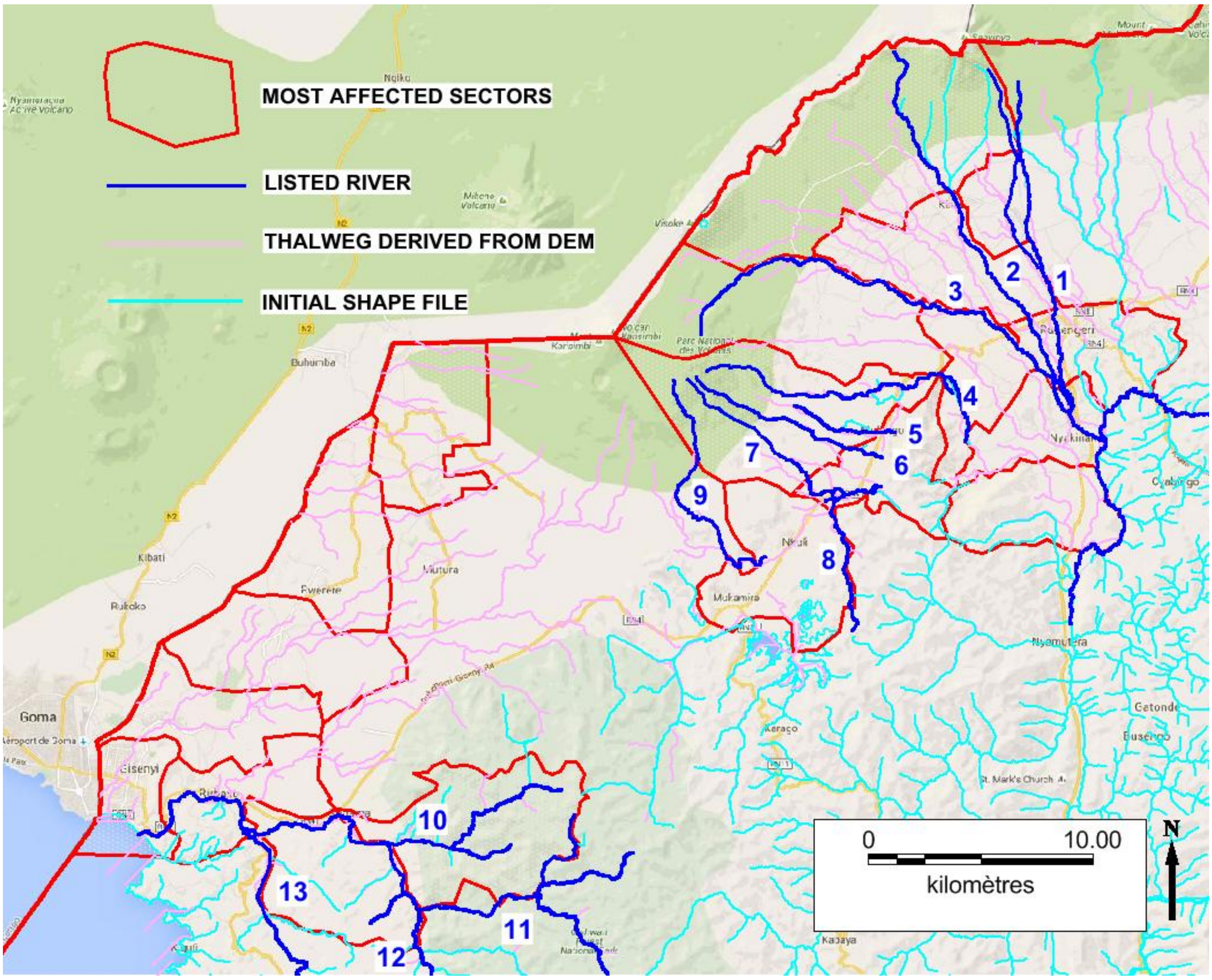


Figure 11: Hydrography of the studied area

We can distinguish three different series of catchments:

- The North-East catchment, under the volcanoe's slopes

- The West side of the volcanoes' area where no river is indicated in the existing shape file. However, the DEM data lead to draw plenty of depressions where it is probable that there is flow after raining.
- The South-West catchment, partly constituted by the Gishwati forest national park.

The different rivers listed are the following ones:

1. Rwebeya River
2. Muhe River
3. Suza River
4. Mudakama and Mutobo Rivers
5. Murufurwe River
6. Rungu River
7. Nyabitondore River
8. Kinoni River
9. Bikwi River
10. Karambo River
11. Bihongoro River
12. Sebeya River
13. Pfunda River

They are precisely analysed in chapter related to site visits.

1.4.3 Geology

Geology is known thanks to the shape file (GIS) given by RNRA (IWRM department).
The following map shows that the ground consists essentially of volcanic rocks then of granitic rocks and some gneiss.
Some very little areas are composed of swampy zones with clays dominant or alluviums.

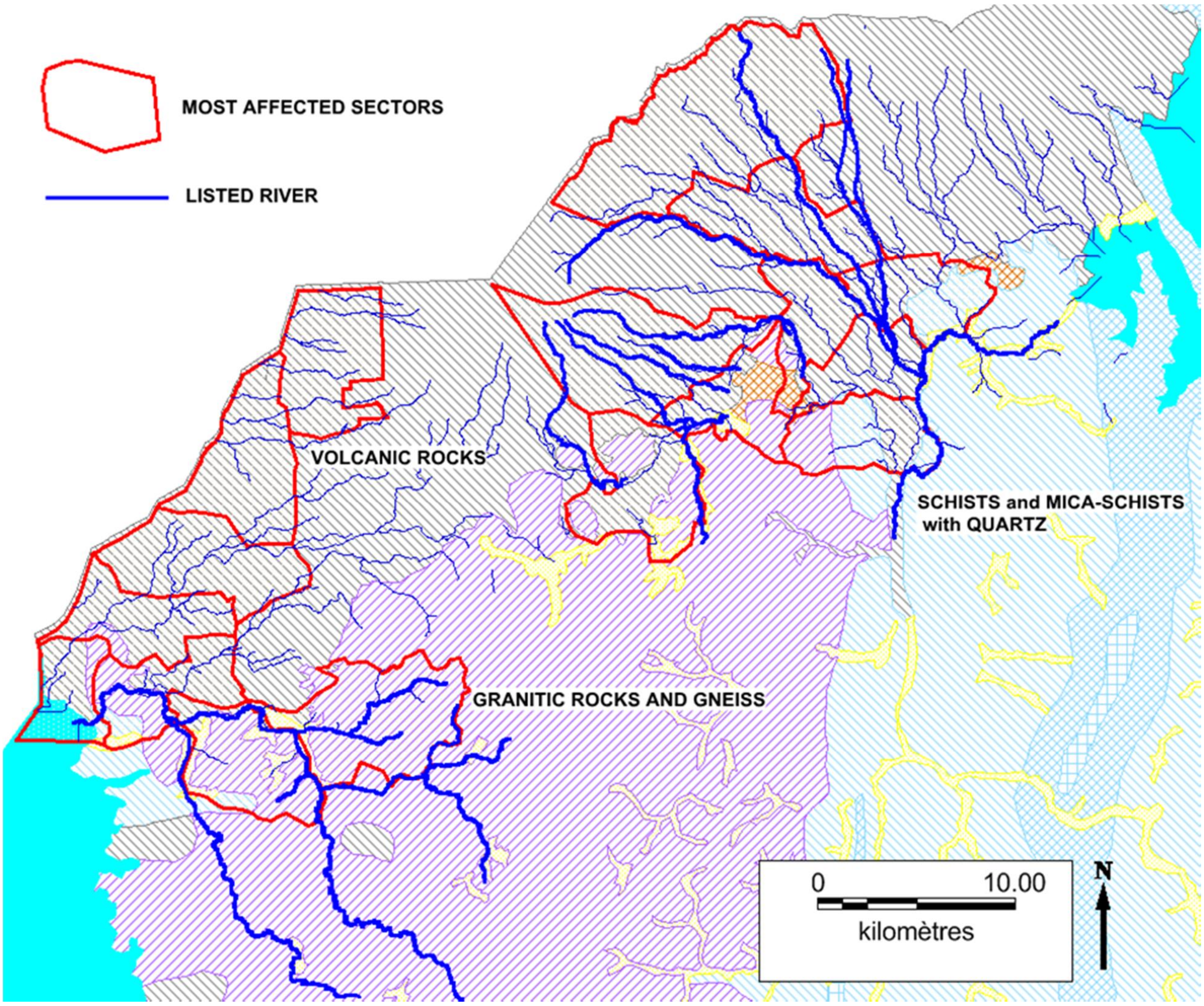


Figure 13: Geology of the volcanoes region

So, the North-East and West river basins are on volcanic rocks and the South-West on granitic rocks.

1.4.4 Land cover

Land use maps have been prepared for the NWRMP with the following classes:
natural forest;
natural open land;
forest plantation;
rainfed agriculture;
natural wetland (65 % if natural vegetation or more);
irrigated/agricultural wetland (less than 65% of natural vegetation);
built up area;
open water.

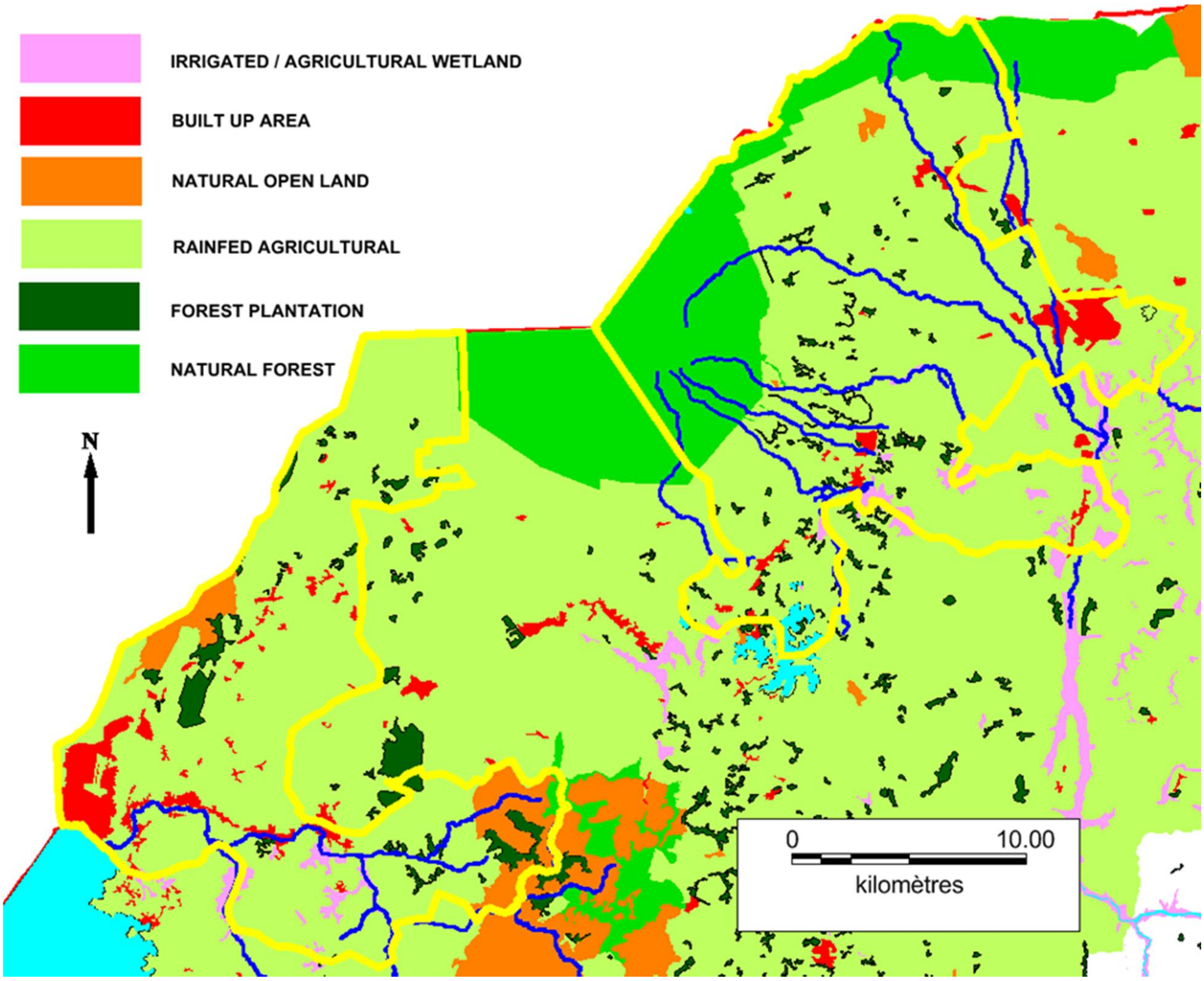


Figure 15: Land cover in the volcanoes region

Except on the upper part of the river basins, covered with sparse forests, the major part of the studied zone is occupied by crop land.

1.4.5 Demography

With about 10.6 million people (4th Population and Housing Census, 2012) and a surface of 26 338 km², the physiological density (number of people per unit area of arable land) is 415 inhabitants per square kilometre.
In the three districts object of this study, thanks to the fertility of the land, the mean density is as follows[1]:

- Musanze District: 600 to 1000 inhabitants/km²
- Nyabihu District: 500 to 600 inhabitants/km²
- Rubavu District: > 1000 inhabitants/km²

The detailed density per sector is shown on the following map.

[1] Rwanda State of Environment and Outlook Report 2015

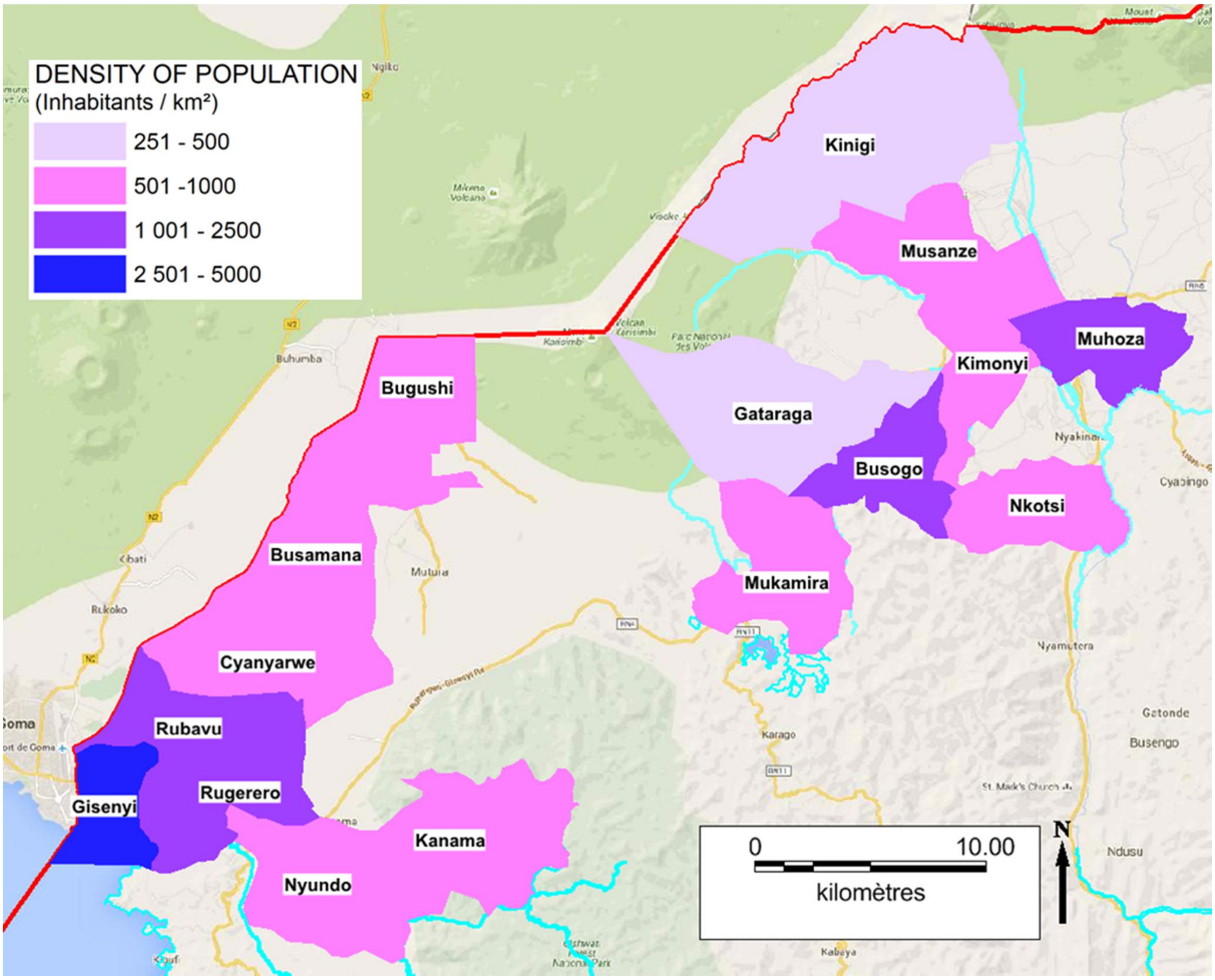


Figure 17: Population density in the volcanoes region

1.5 Report's structure

The structure of the report is the following one:

- Chapter 2: Site visits on North-East river basins
- Chapter 3: Site visits on South-East river basins
- Chapter 4: Analysis of extreme rainfall
- Chapter 5: Hydrological study of North-eastern volcanic basins
- Chapter6: Hydrological study of Sebeya River basins
- Chapter 7: Maps of flood prone areas
- Chapter 8: Mitigation works

1.6 Methodology

The methodology followed has been as followed.

1.6.1 Data collection

The data were collected with the administration (IWRM - RNRA).
They concerned:

- Previous studies

- Topography
- Hydrology
- Land use
- ...

They were supplied in various forms: text files, pdf, GIS.

1.6.2 Field survey

Field surveys have been investigated by car and by walking as it is not accessible by car.
The scope of this phase were as follows:

- interview of the people living near the rivers and possibly submitted to flood in order to know:
  - Which flood do they remember?
  - What was the level reached during these floods?
  - What do they do in case of flood?
  - Were there some modifications of river configuration (natural, human made)?
  - ...
- Measurement of the cross sections near the place;
- Estimation of roughness of the bed ;
- Measurement of the possible existing structures having influence on the flows as culvert, weir, bridge, ...

1.6.3 Hydrology

The objectives of the hydrological study are the knowledge of the characteristic rainfall and discharge.

1.6.3.1 Rainfall analysis

Characteristic rainfalls have been studied thanks to samples of daily rainfall at some rain gauges at the vicinity of the catchments.
We have analysed annual maxima and values over threshold thanks to a specific method established by ARTELIA since more than 20 years.

1.6.3.2 Discharges analysis

For catchment where there is no data we have used the information obtained thanks to field surveys.
For each event found during the field survey we have determined the associated discharge and estimated the period of return. We have associated intervals of uncertainty in order to assess different rectangles of uncertainty.
All these rectangles of uncertainty allowed us to draw a graph and to determine characteristic discharges.
For Sebeya River where there are some data registered, we have used these one to proceed with a statistic analysis.
Finally, we have built hydrological model in order to compare those different results and to estimate usefulness and validity of such a tool.

1.6.4 Flood mapping

Flood prone areas have been assessed thanks to different methods:

- hydraulic modelling
- expertise

1.6.5 Flood risk reduction measures recommendation

Proposed mitigation works have concerned:

- Bank protection
- Bridge fixing
- Deposition area

- River training
- Levees
- Diversion channel

Other more general interventions have been proposed.

1.7 Overview of stakeholders

Some stakeholders have been met during the different missions:

- ü INES (Institut d'enseignement supérieur de Ruhengeri)
  - Ø A first meeting in May 2016 allowed us to get some information on their 4 years' program and of the studies already done. And to present our own study's program.
  - Ø A second meeting in August 2016 permit us to propose to involve students in the field visits, in order to show them the procedure we followed.
- ü Musanze's Mayor
  - o Met randomly during a site visit on 17th of August: the interview was too quick to gather the necessary information.
  - o No other meeting was able to be held in spite of two appointments because of its workload.
- ü RTDA (Rwanda Transport Development Agency - MININFRA)
  - o On September 12th, two attempts to meet have been made this day: in Rubavu local office and in Kigali head office. Unfortunately, they were unsuccessful.
  - o On November 1st, a presentation has been made in front of representatives of RTDA to inform them about the ongoing study, especially about the proposed mitigation works.
- ü Water Resource Monitoring Network Officer in RNRA
  - Ø We met Marc Magnifica in order to get hydrologic data

2. Site visits – North-East river basins

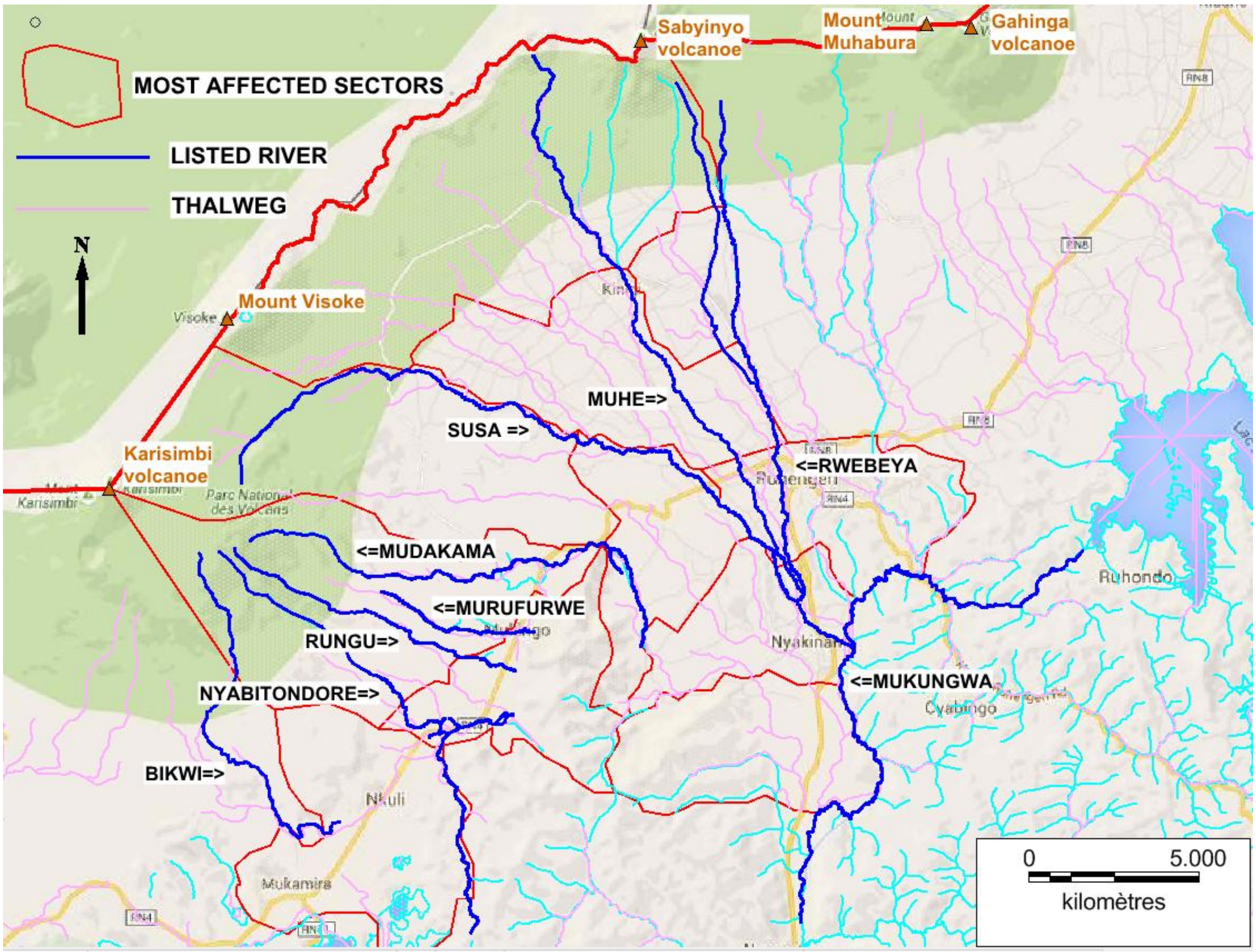


Figure 18: North East river basins' map

This chapter reports what has been seen and heard during the field visits.

2.1 Rwebeya River

2.1.1 Description

Rwebeya River is the main stream concerning Musanze's downtown. It flows from North to South similarly to all nearby rivers.

From upstream of Musanze to the confluence with the Susa River, the average slope is 3.2% irregularly distributed (varying from 2% in Musanze's urban area to 9% downstream of this one).

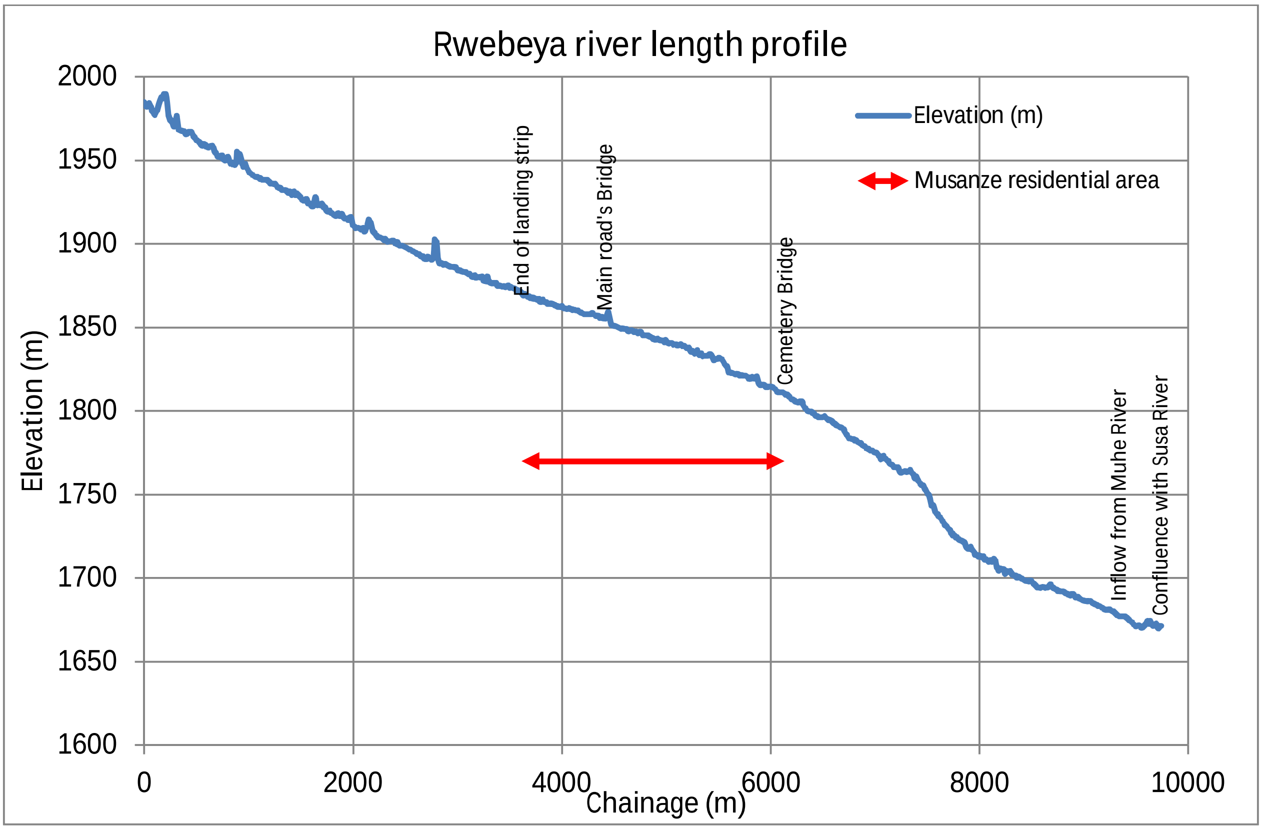


Figure 19: Rwebeya longitudinal profile

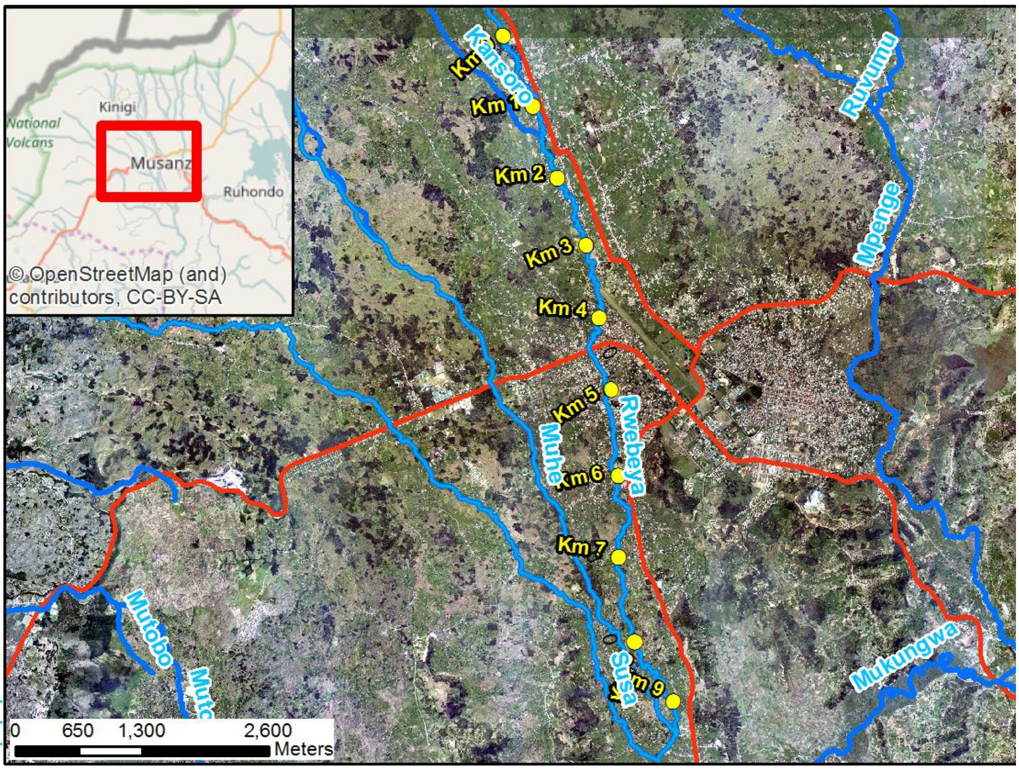


Figure 20: Rwebeya location of abscissas

The field visits also highlighted the variations of the river bed size:

- Upstream of Musanze, the river bed is very deep (~10m); some canyons have even been dug into the bedrock.
- In the crossing of Musanze's urban area, river training has been gradually made since a dozen of years.
- Downstream of Musanze, the river bed becomes globally smaller with an insufficient capacity that triggers overflows for frequent flooding events.

2.1.2 Raised issues

2.1.2.1 Erosion

Upstream of Musanze, the main issue is erosion: the important depth of the river bed generates high slopes embankments which are unstable when a flood occurs. Many houses are threatened; some of them have been destroyed.

The maps below show an aerial view of the river at two different times: 2008 (left) and 2014 (right): we can notice that two houses vanished meanwhile due to the collapse of the bank.

Figure 21: Comparison of two aerial views (2008 and 2014)

The risk of erosion decreases in the urban area of Musanze because of the edification of many abutments. Downstream of Musanze, the erosion risk increases again, especially upstream of the confluence with river Muhe.

2.1.2.2 Sediment transport

Another issue is the sediment transport. The field visit, performed during the month of August 2016, has shown no signs of massive quantities of sediments in the river bed at this time. However, inhabitants met during the visit mentioned two areas where sediment depositions take place:

- Km 3.6 ± 0.5 (around landing strip)
- Km 9.5 (upstream of confluence with Susa river)

Checking aerial views from 2008 confirmed these testimonies: at this time the flood season brought amount of sediments which appear clearly on the pictures. The pictures below show two different states: in 2008, the bed was full of sediments whereas the bed was empty in 2016.

Figure 22: Sediment transport phenomenon on Rwebeya river (upstream of Musanze)

The deposition areas are located right after large erosion zones. The two deposition areas seem to be disconnected because little sediment transport has been noticed between them.

Sediments from the downstream deposition area (Km 9.5) have been extracted in 2011 for aggregates. This area is shown in its 2008 and 2016 states on the aerial views below.

Figure 23: Comparison of 2008 and 2016 states on Rwebeya's downstream deposition area

The change in bed's axis (especially length shortening) leads to a lowering of the upstream bed.

2.1.2.3 Overflows

No overflows occur upstream and when crossing Musanze's urban area, this is due to the important depth of the river bed.

Two places are concerned:

- Downstream of the cemetery bridge (Km 6.2): the bed cross section is insufficient even for common floods and overflows occur over the right bank. The water spills then into a parallel thalweg and do not returns immediately to the main channel (see map below).

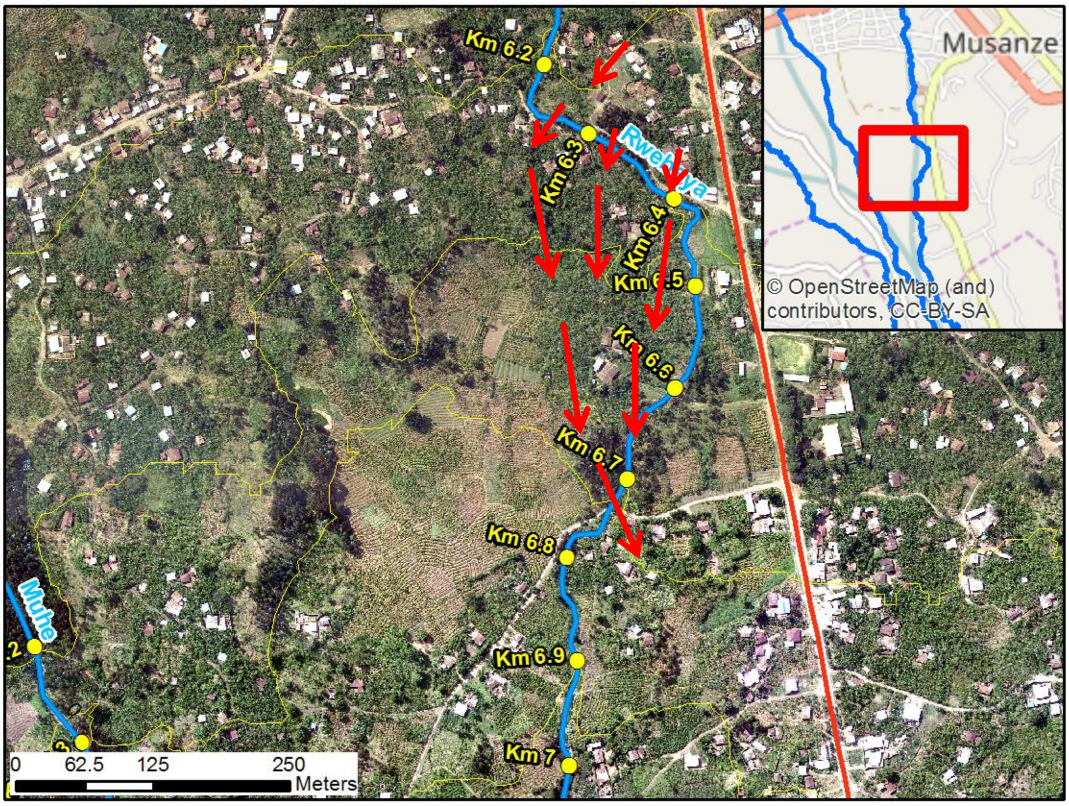


Figure 24: Location of Rwebeya's overflows - site 1

- Downstream of the confluence with River Muhe, overflows occur again, especially over the right bank mixing then with those of the Susa River (see map below);

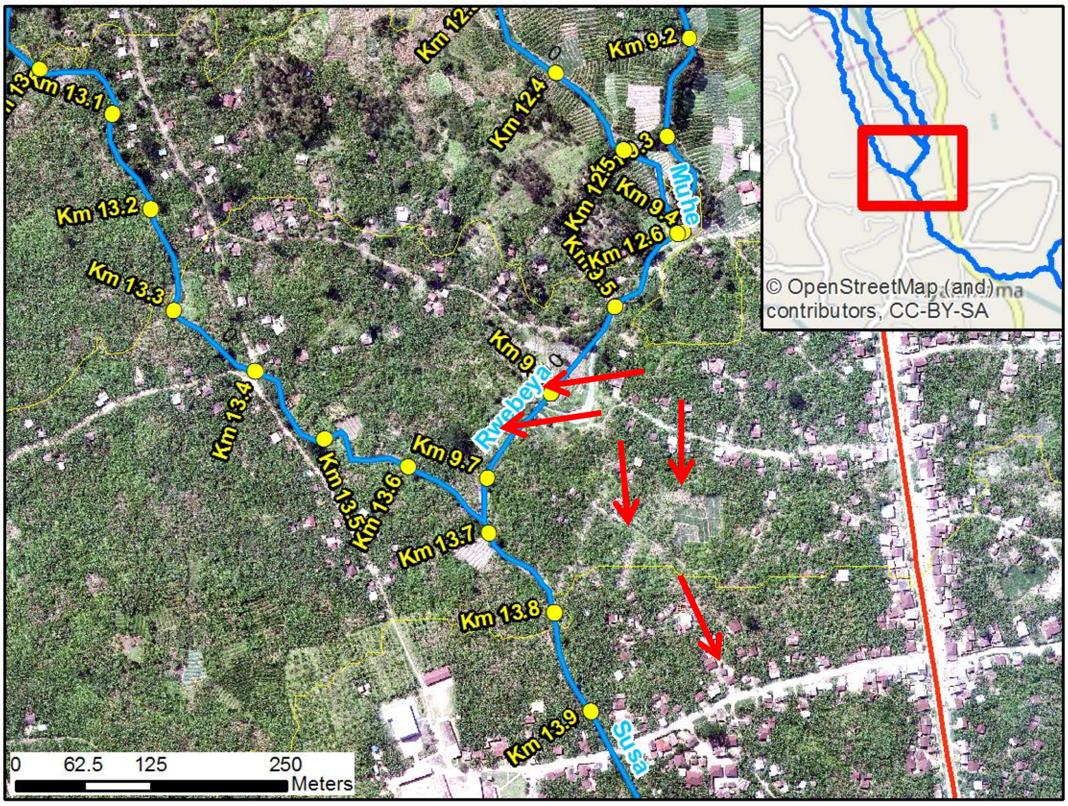


Figure 25: Location of Rwebeya's overflows - site 2

2.1.2.4 Bridges capacities

Most of the bridges offer a good capacity for frequent floods except wooden footbridges (made by local peoples) which are often destroyed.

2.1.3 Floodplain mapping

Determining the flood prone areas on Rwebeya River will be done mostly by using geomorphology expertise and informations gathered. Indeed, accurate hydraulic modelling can't be made on such a river because of too many uncertainties. Most of the time, discharges can't be accurately estimated due to the changes of bed levels (at different times, a same water level may not correspond to a same discharge!).
Nevertheless, hydraulic modelling has been used:

- Ø At few locations to determine discharge (where bed level is stable);
- Ø In the urban area of Musanze where bed changes are non-existent (i.e. river trained part downstream of the main bridge). This is used to locate potential overflows for 100 years return period flood.

2.2 Muhe River

2.2.1 Description

Muhe River is located western of Musanze's urban area. It flows from North to South similarly to all nearby rivers.
From upstream of Musanze to the confluence with the Susa River, the average slope is 4.3% to 3.2% irregularly distributed (varying from 3.5% in Musanze's urban area to 9% downstream of this one).

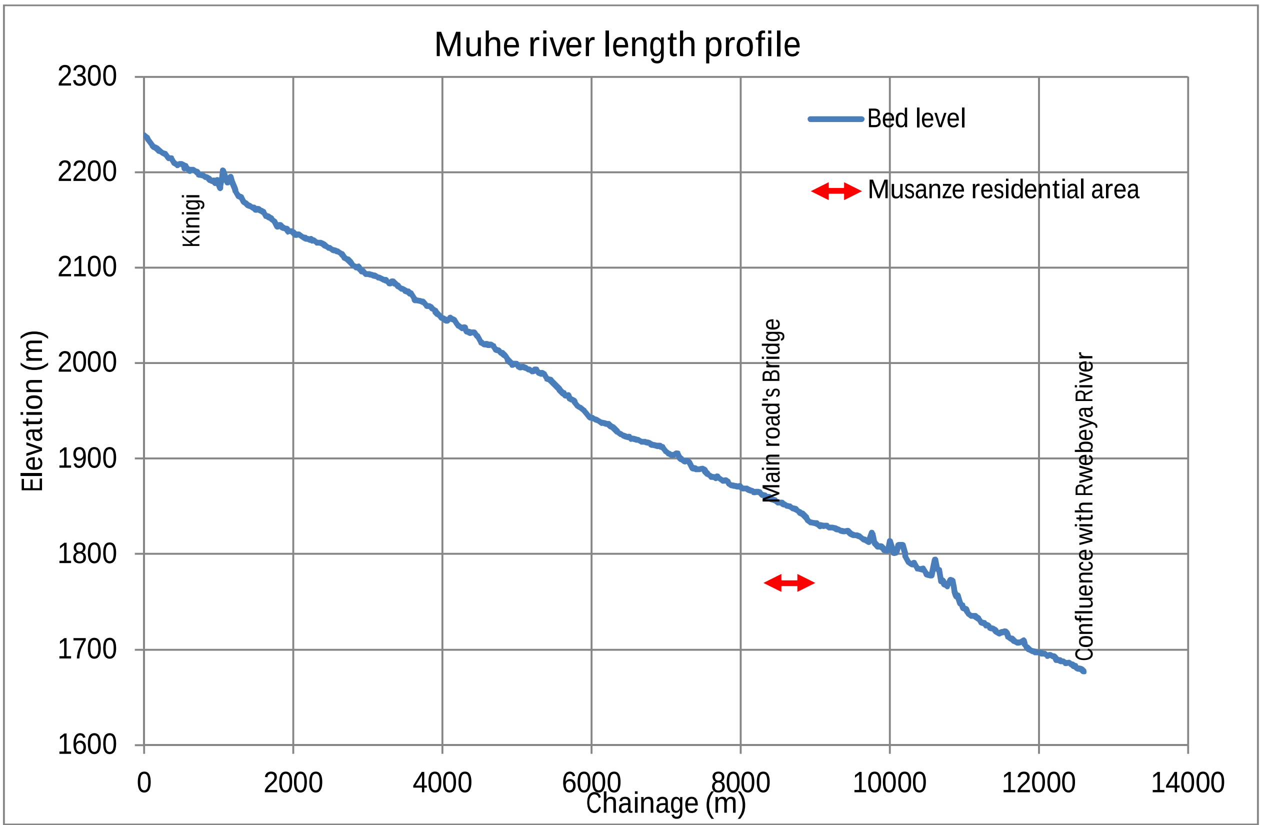


Figure 26: Muhe longitudinal profile

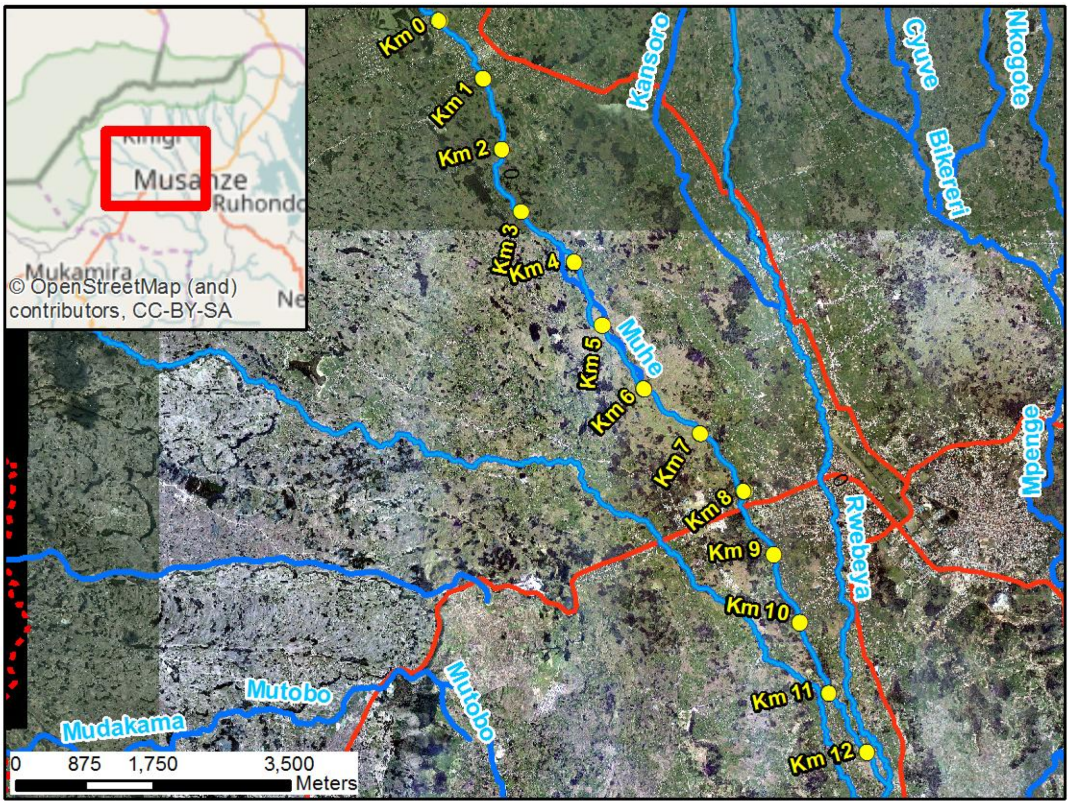


Figure 27: Muhe location of abscissas

2.2.2 Raised issues

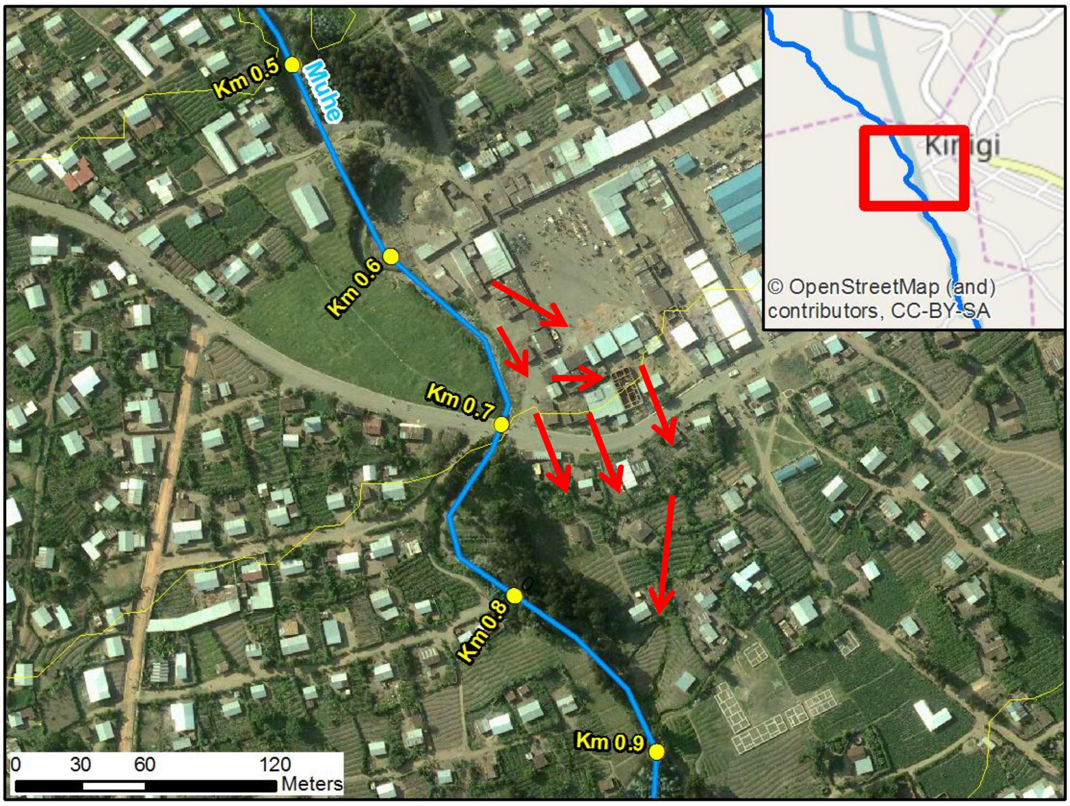
2.2.2.1 Erosion

Erosion appears not to be a major problem on this river. It occurs in some places downstream of Musanze urban area (during and right after the fall in length profile Km 11.000). Upstream on Musanze, the river regularly flows outside its bed, therefore limiting banks erosion.

2.2.2.2 Overflows

Overflows occur almost everywhere on Muhe River:

- Ø In Kinigi, where the market's bridge is overflowed almost each year. Only the left bank is concerned (see below) ;



Ø

Figure 28: Location of River Muhe's overflows - Kinigi

- Ø Between Kinigi and Gisenyi Road NR2: the river divides and merges several times allowing easier overflows in the fields: the water is sometimes detoured into secondary thalwegs and routed to inhabited areas. This phenomenon is due to the lack of soft ground in this area preventing the river from digging a deep bed: in some places, the basalt layer is only 1m below surface, forcing the river to spread horizontally during a flood.

  About 2km downstream of Kinigi, overflows occur on the right bank, cross the track and flow into another thalweg which belongs to Susa catchment. Spilled water may reach Susa or infiltrate, but this information is totally unclear (lack of witnesses). Anyway, River Muhe for sure loses water in this sector.

Figure 29: Muhe river: lack of deepness due to close hard basalt layer

- The bridge of Gisenyi Road is under-dimensioned, triggering frequent left bank overflows (almost every year). Spilled water then concerns an entire neighbourhood (see below);

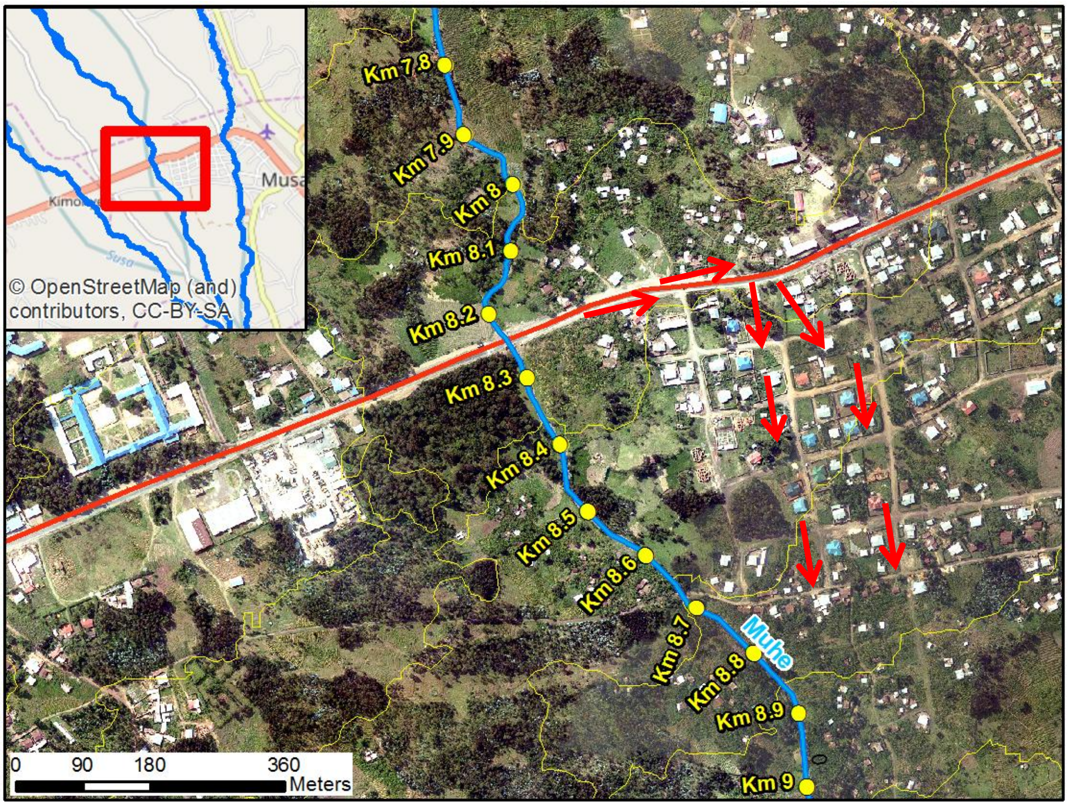


Figure 30: Location of River Muhe's overflows – Main bridge

- Upstream of confluence with river Rwebeya (Km 12.1) overflows occur both sides. Right bank, a part of the spread water is routed to Rwebeya River which is locally deep and offers enough capacity (see below)

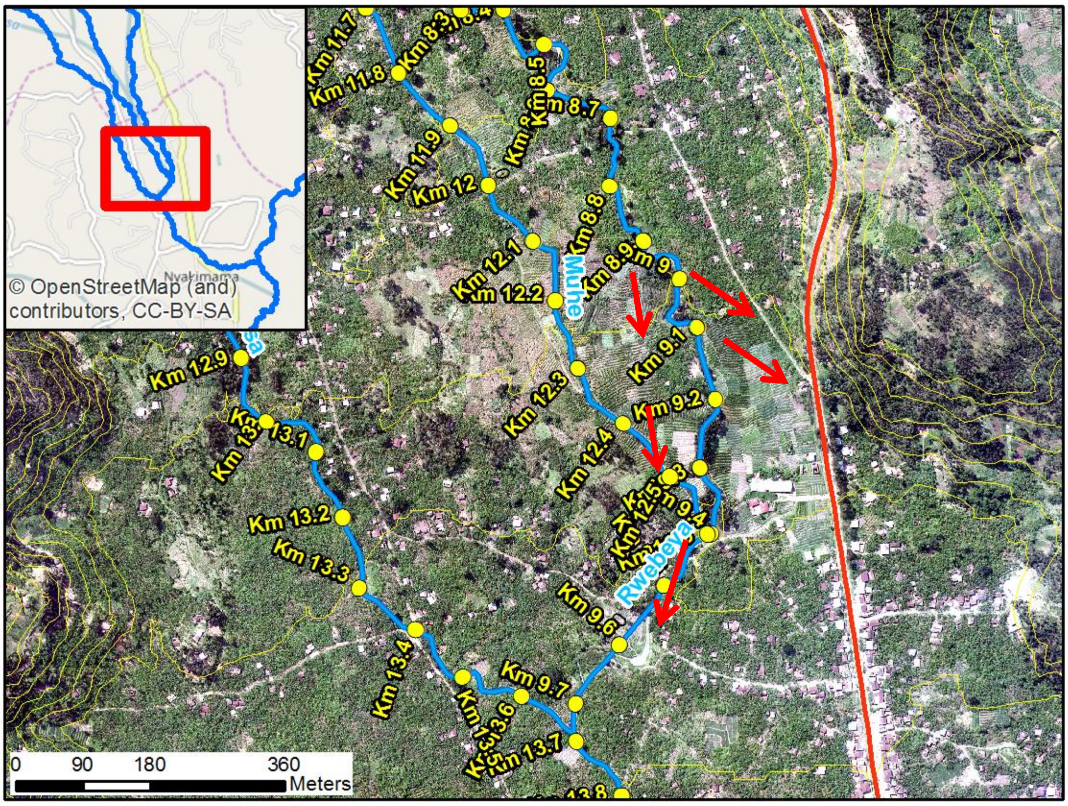


Figure 31: Location of River Muhe's overflows – Confluence with Rwebeya

These several flooded locations prevent us from finding a cross section where all the discharge flows through and which have been witnessed during a flood by local people.

2.2.2.3 Bridges capacities

From Kinigi market's bridge to the end of the River, none of the hydraulic structures surveyed is offering enough capacity, even for frequent floods as we have been told thanks to testimonies and we have checked with hydraulic calculation (for 100 years return period discharge).
Notice that:

- Most of them induce limited damages because the water spreads locally and immediately returns to the channel.
- The bridge crossing the main Road to Gisenyi (Km 8.300) is inducing overflows on the left bank: the water then spreads along the road and floods an entire neighbourhood. Moreover, the main culvert (corrugated metal pipe) is severely damaged and is currently being eroded externally. The bank supporting the road is threatened.
  - NOTA BENE: Since our field visit, the corrugated pipe has been repaired.

Ø

Figure 32: Muhe river: brige under the road to Gisenyi (view from upstream)

2.2.2.4 Caves

A large cave has been located around the channels of rivers Muhe and Susa. This cave is tunnel-shaped and its axis is following the directions of the rivers and the former lava flows. The dimensions are very important (around 10m in diameter).

No evidence of link between rivers and caves has been witnessed in this place, but they may play an important role in infiltrating overflows elsewhere (e.g. Mutobo/Mudakama river).

Figure 33: Cave between Susa and Muhe rivers (partially collapsed on the right picture)

2.2.3 Floodplain mapping

Determining the flood prone areas on Muhe River will be done using geomorphology expertise and information gathered.

Indeed, modelling the river would not enhance the comprehension of the flood dynamics and the accuracy of the mapping because of the complexity of the configuration: downstream of Kinigi, the river widely overflows in the fields as the river channel is often following a kind of ridge. Moreover, a part of the spilled water doesn't return to the river bed and simply infiltrates.

2.3 Susa River

2.3.1 Description

Susa River is located western of Musanze's urban area. It flows from North to South similarly to all nearby rivers. The River flows from the eastern face of Karisimbi volcano, contrary to Muhe and Rebeya rivers which flow from Sabinyo volcano, in the north.
The slope of the river varies from 3% in Muko sector (confluence with Rwebeya) to 5% and more in Musanze's urban area. Between Km 11.5 and Km12 slope rises up to 15%.

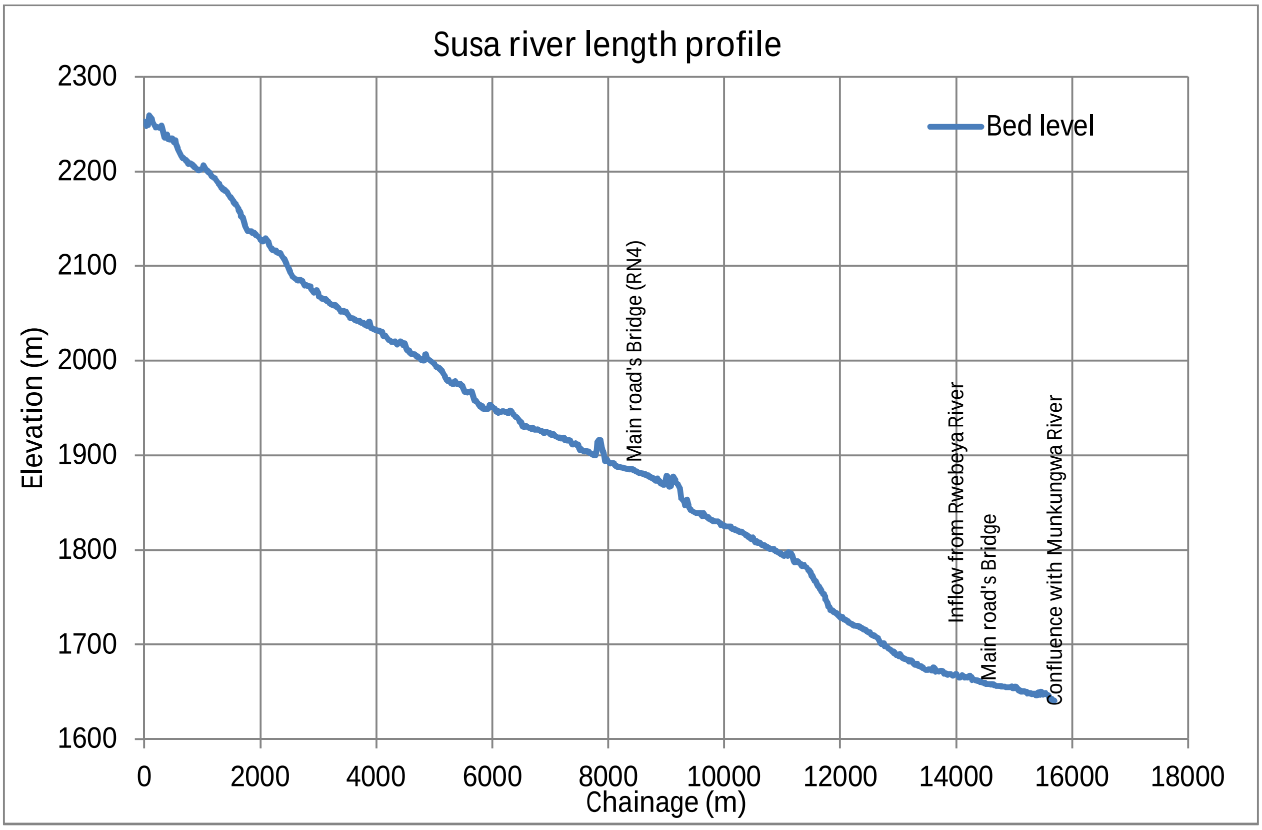


Figure 34: Susa longitudinal profile

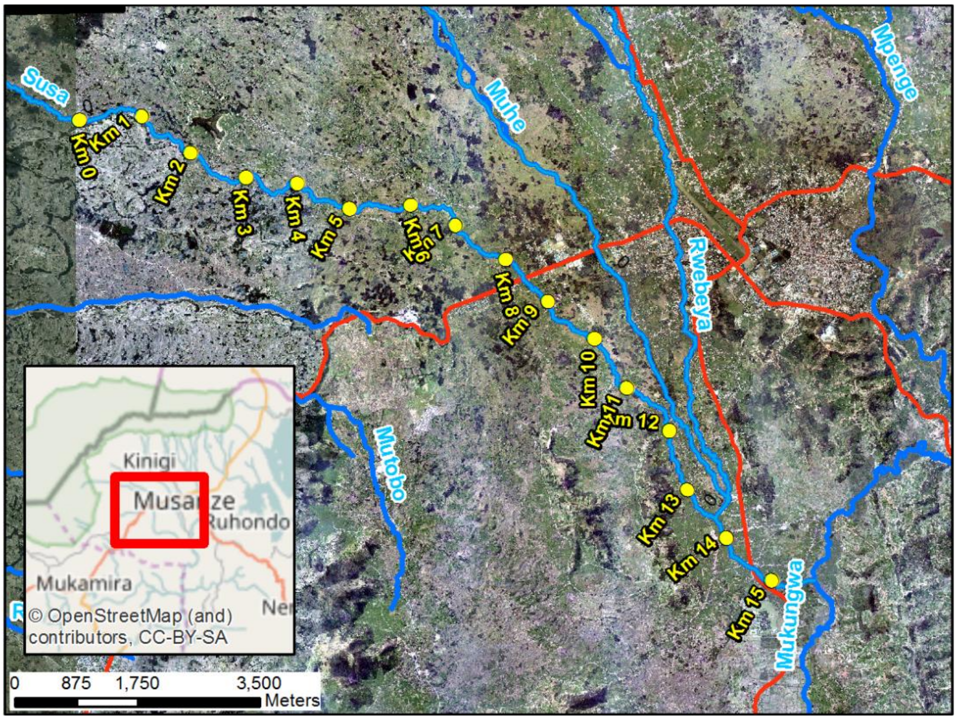


Figure 35: Susa location of abscissas

2.3.2 Raised issues

2.3.2.1 Overflows

Overflows occur almost everywhere on River Susa due to the lack of capacity of the channel. Indeed, the presence of hard basalt layer under 70 cm of erodible topsoil prevents the river from naturally digging a channel.

Figure 36: River Susa: rocky part is the main channel: no deepness here!

Main locations of overflows are listed below:

- Gisenyi road's Bridge: insufficient capacity of the culvert enables water to flood the road and houses around;
- From Km 12.2 to 14, the river bed of the river is even smaller than the one upstream. Overflows occur almost everywhere in the fields. Some houses are lightly flooded. The road following the river along the left overbank collects a part of these overflows (see below);

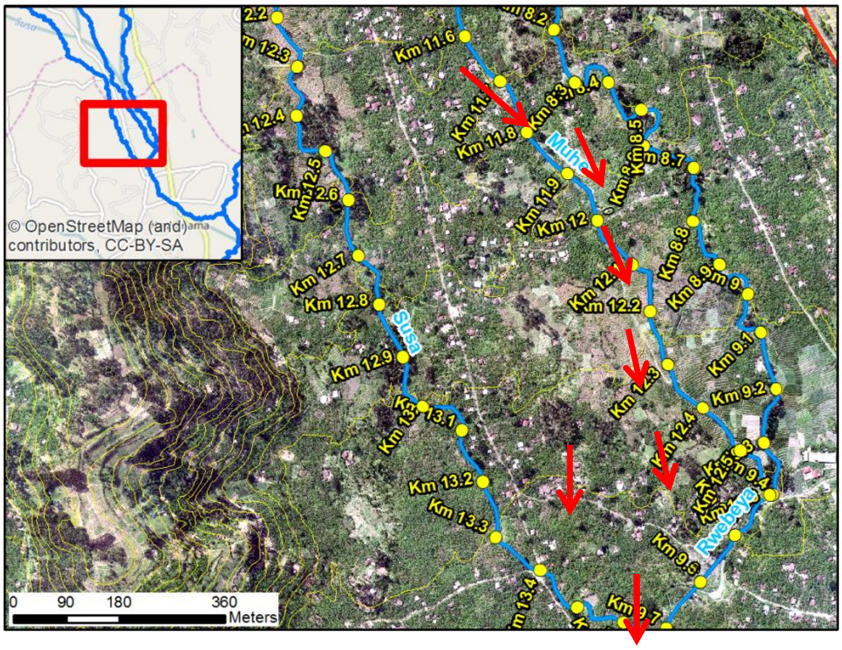


Figure 37: Location of River Susa's overflows – Km12 to Km14

- Bridge Km 13.7 overflows, triggering overflows which continue their way to school "Groupe scolaire Muko". The school is partially flooded;

- Bridge Km 14.6 (Road Musanze – Military academy): the structure is frequently overflowed. It is due to its lack of opening worsened by sediments deposition. An important area is flooded around, water spills to the military academy, 500m south (and even to the Musanze Polytechnic, another 1km south).

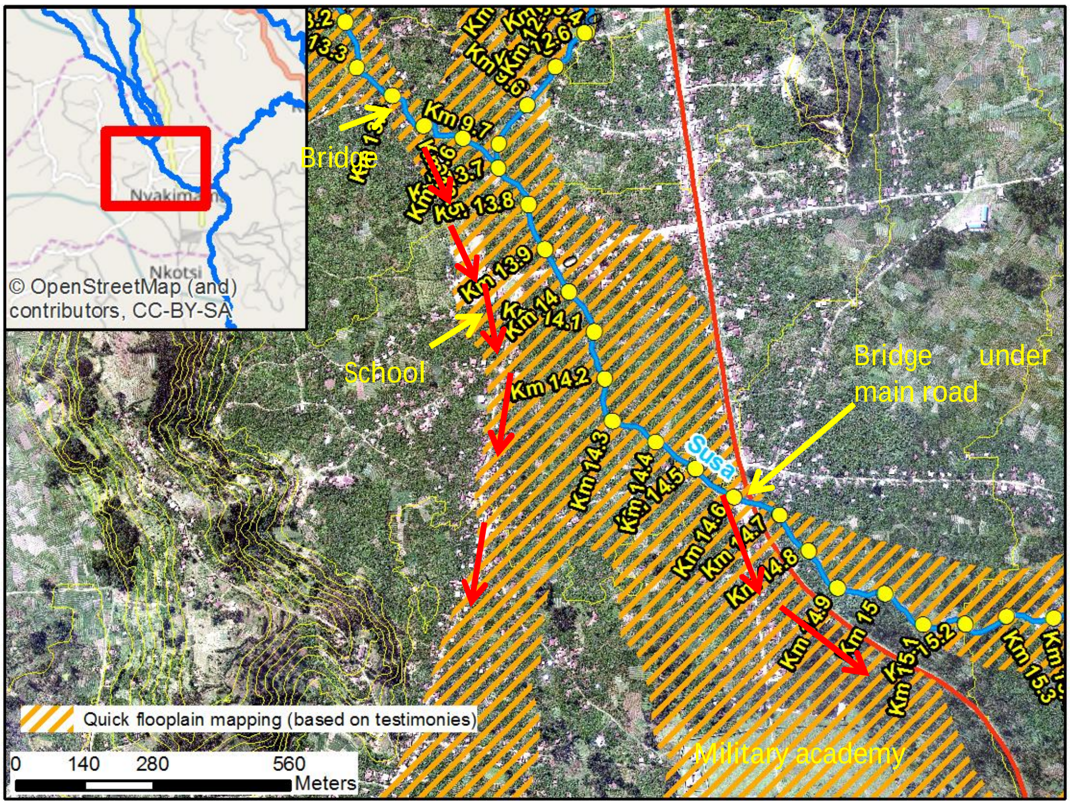


Figure 38: Location of River Susa's overflows downstream (Approximate flood prone area in hatches)

2.3.2.2 Sediments deposition

Sediment deposition is an important issue on the river, especially in the downstream part (Muko neighbourhood). Most of the sediments are brought by rivers Rwebeya and Muhe. The bed level rises after each important flood and river and bridges capacities are reduced. Afterwards, a dredging is necessary.

Figure 39: Partially blocked culvert on river Susa (main road to military academy)

2.3.2.3 Caves

Not a direct problem per say, but may contribute to the important seepage witnessed in the fields. See chapter 2.2.2.4.

2.3.1 Floodplain mapping

Determining the flood prone areas on Susa River will be done using geomorphology expertise and information gathered.
Indeed, modelling the river would not enhance the comprehension of the flood dynamics and the accuracy of the mapping because of the complexity of the configuration: downstream of the road to Gisenyi, the river widely overflows in the fields as the river channel and a part of the spilled water simply infiltrates in the fields.

2.4 "River" between Susa and Mutobo rivers

DEM10's analysis show us that it seems that a river is located between rivers Susa and Mutobo. In fact, it does not exist as a stream in the downstream areas (nevertheless, some gullies can be seen in the very upper catchment area, disappearing progressively).
No evidence of flow has been recorded in the downstream thalweg. No hydraulic structure has even been constructed under the road NR2 when it crosses the thalweg.

Figure 40: Panoramic view of the thalweg nearby road NR2

Downstream of the road, the thalweg no more exists.

Figure 41: Downstream of the road

2.5 Mudakama / Mutobo River

2.5.1 Description

First of all, it is necessary to clarify the uses of names in this catchment area:

- Mutobo: permanent stream coming from a spring, 2 km upstream of the main road NR2. It does not participate significantly to the floods;
- Mudakama: Gully coming from the volcano slopes and providing almost all the discharge while a flood (mixing then with Mutobo).

Figure 42: Mutobo springs

From the Mutobo spring to road NR2, the mean slope is around 3.5%.

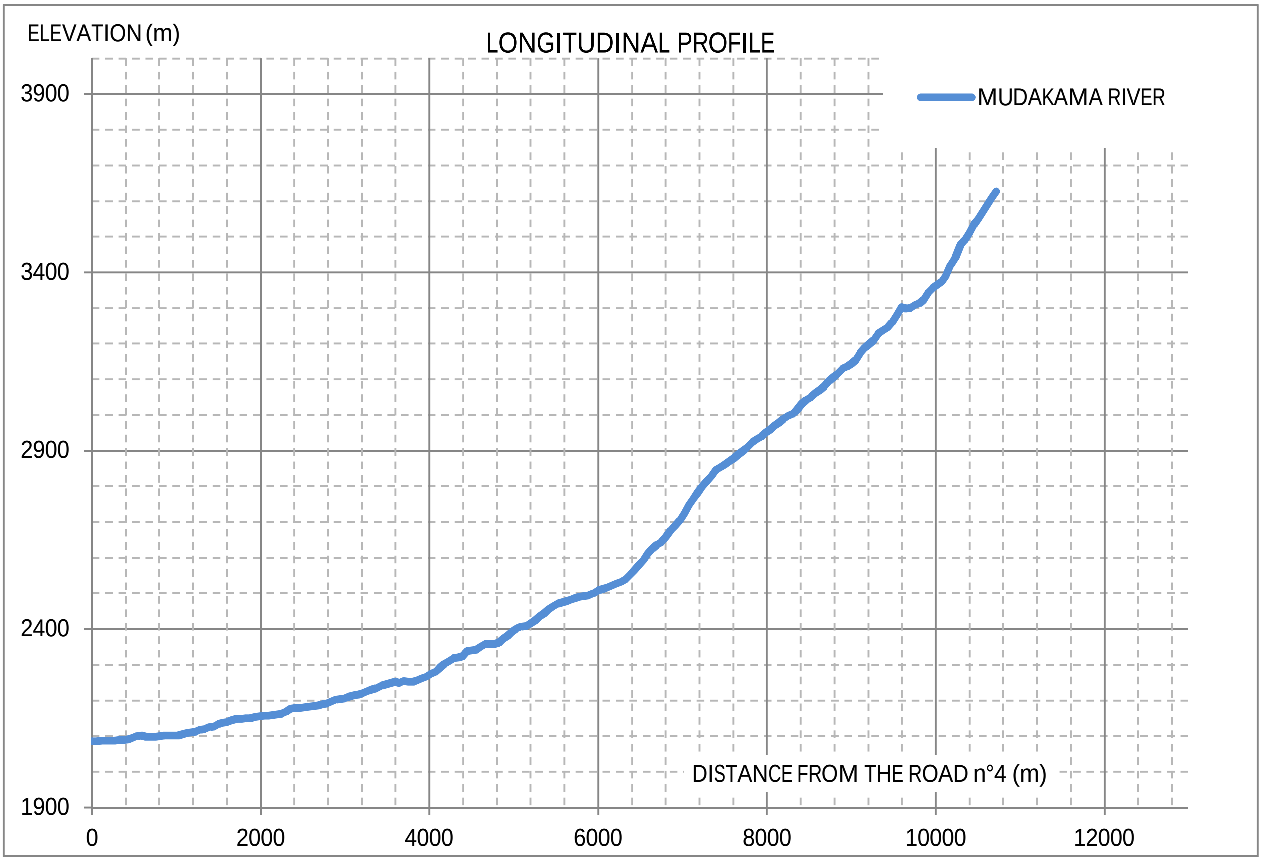


Figure 43: Mutobo longitudinal profile

Downstream of the road, the slope increases (waterfalls) and a part of the flow is diverted to a penstock for hydropower. Afterwards, the river split in two reaches: one is entirely disappearing into an important cave; the other one fills endorheic lowland.

2.5.2 Raised Issues

2.5.2.1 Overflows

Following the site visits, the main areas concerned by overflows from river Mutobo are listed below:

- Around and downstream of the drinking water plant (km 1.5): at this place, the valley widens and the first overflows appear. In 2016, the plant has been lightly flooded. The water then spills into the flood plain and accordingly to testimonies, all the flow (except seepage) returns to the main channel to flow through the culvert under road NR2. (see map below).
  Downstream of the culvert, houses have been flooded (left bank).

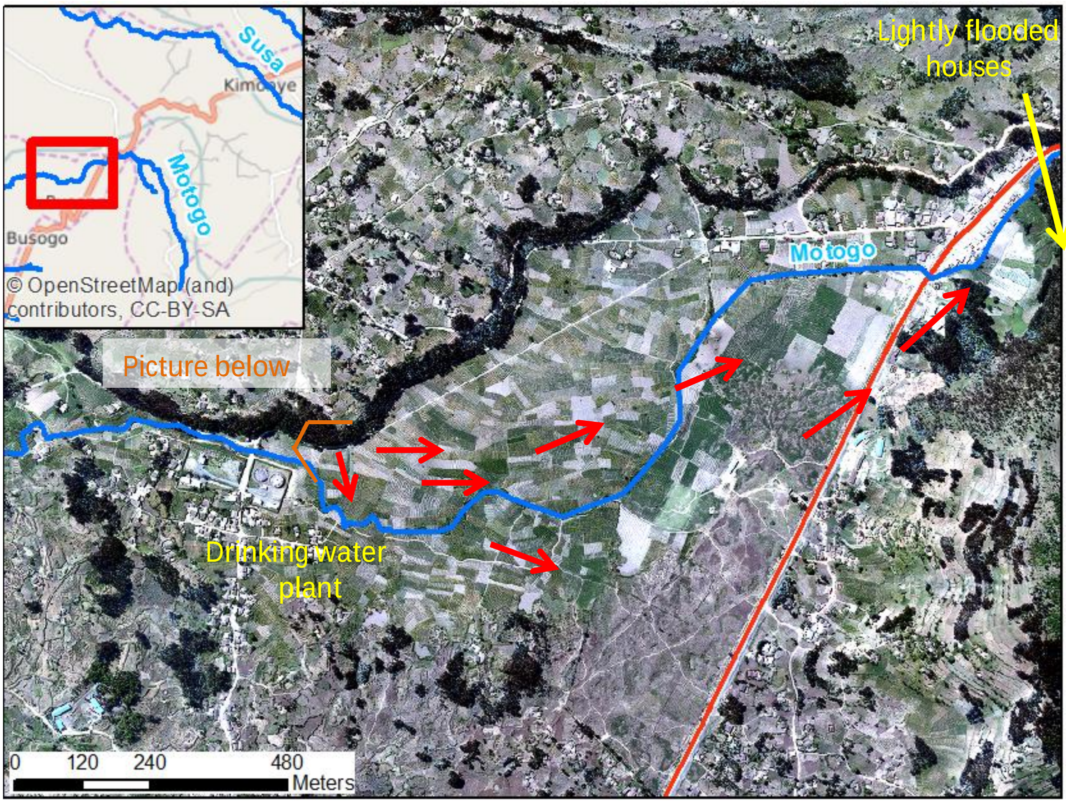


Figure 44: Location of River Mutobo's overflows (may 2016) – Upper area

Figure 45: River Mutobo next to drinking water plant (looking downstream)

Ø After splitting, river Mutobo regularly spills into the fields nearby the bed. The left side reach cross an inhabited area and overflows occur in the village. A school is threatened despite the presence of a dike. Globally the lack of capacity of the channel enables overflows almost everywhere. The road on the left bank also conveys spilled water. Both of the reaches end in caves.

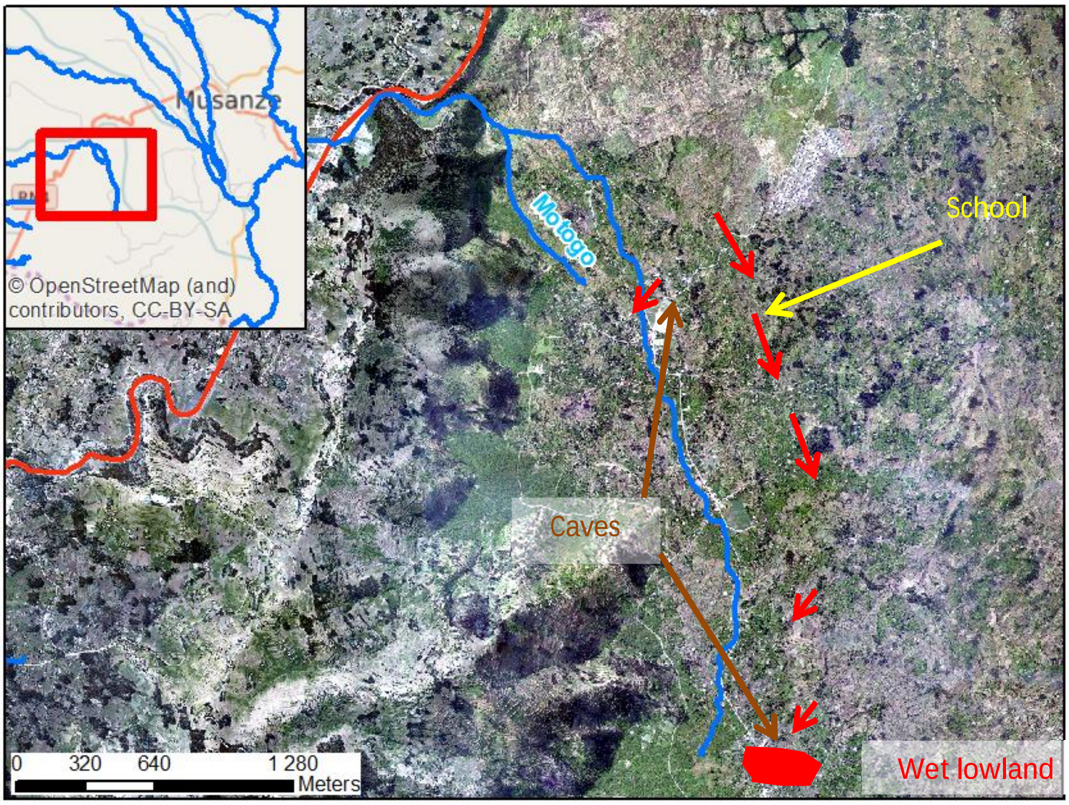


Figure 46: Location on main overflows on river Mutobo

Figure 47: Mutobo left reach: dike overflowed in 2014

2.5.2.2 Caves

Both of the reaches of river Mutobo end into caves:

- The right branch (when looking downstream) enters a large cave. The capacity of the cave seems to be important and could be explained by the permanent flow entering it and keeping carving the tunnel.
- The left branch is longer than the previous one and also carries less water. It ends into a wet lowland where two caves absorb water. Their capacities are very limited: local residents told that it takes months for the lowland to empty after raining season and that even during dry season the level can rise again (just because of the variation of irrigation needs).

Figure 48: Outlet caves of river Mutobo

2.6 Endorheic Rivers: Murufurwe, Rungu, Kinoni & Nyabitondore, Bikwi

2.6.1 Description

These rivers are all endorheic that means they have no exit that is no confluence with other river or lake. Former lava flows from the Karisimbi volcano shut some valleys of a pre-existing range of hills, giving birth to these endorheic areas.
Their water is progressively infiltrated in the volcanic ground. At their extremities, they are diverted to different caves which absorb more or less all the discharge.
However, in case of extreme flood as it occurred in May 2016, the lowlands nearby the caves are flooded.

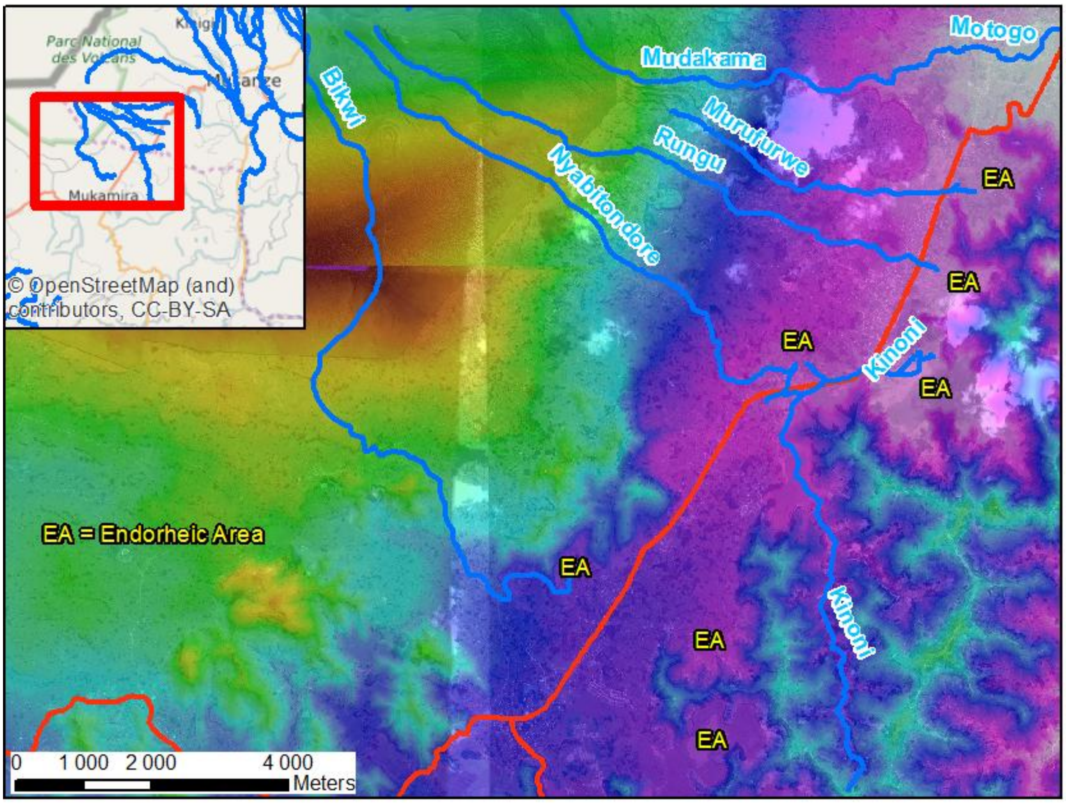


Figure 49: Location of main rivers and endorheic areas

The slopes just upstream of the floodplain are around 2 or 3%.

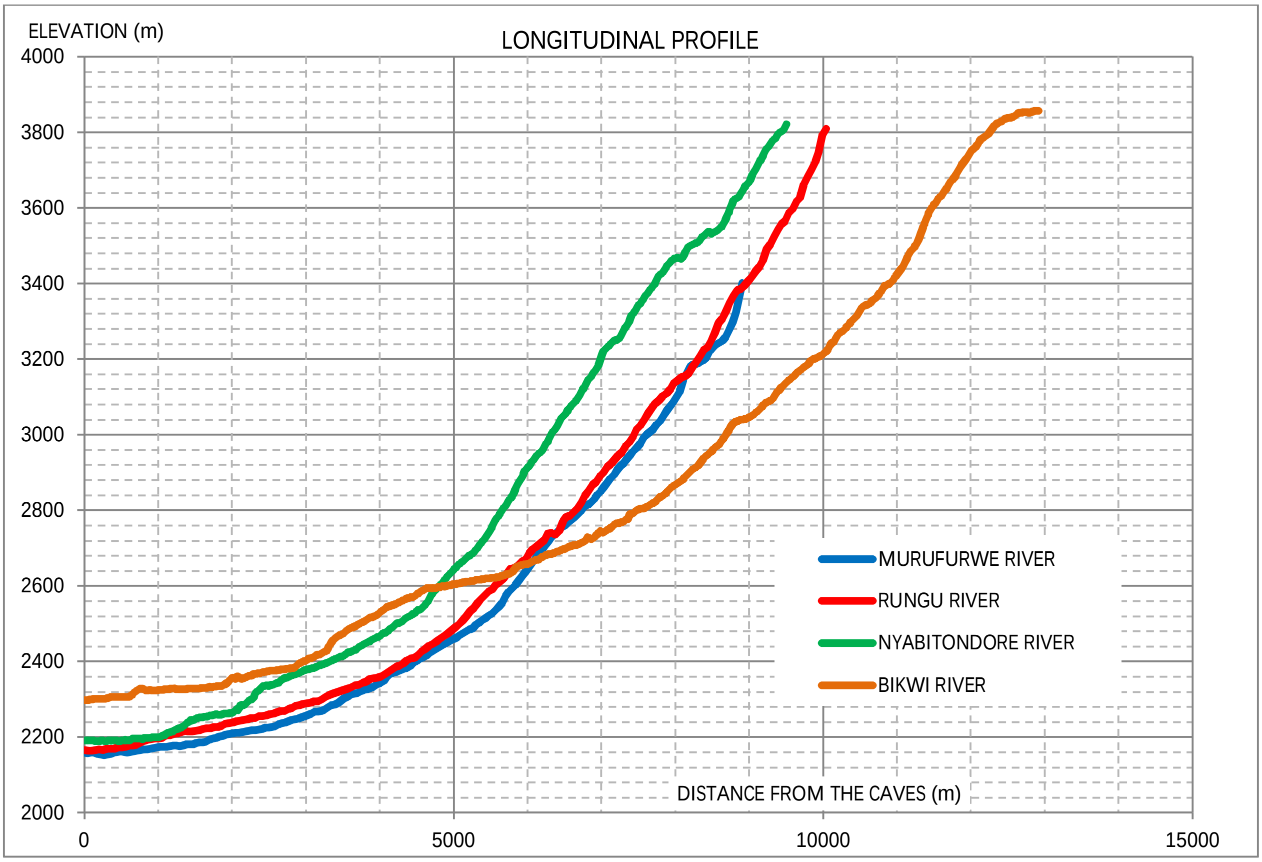


Figure 50: Endorheic rivers longitudinal profile

2.6.2 Raised issues

2.6.2.1 Erosion

Erosion phenomena are a minor issue on this sector. According to what has been seen during the site visits, no building is yet threatened by erosion of riverbanks.
However, some erosion locations can be listed below:

- Rivers Murufurwe and Mungu: both of these have a similar morphology (i.e. gullies crossing fields with soft topsoil) and erosion of the banks is recurrent.
- River Nyabitondore: downstream of the river, a very steep part has severely been eroded. According to witnesses, the river used to end into caves located on a plateau above. The caves have been blocked for some years and people diverted the river to a thalweg in order to avoid overflows: this action concentrated the water and an important erosion phenomenon is occurring. Large amount of stones are transported to the fields downstream: this erosion has no reason to stop as long as the river bed do not reach equilibrium.

Figure 51: Nyabitondore River (view to upstream)

- Ø River Kinoni: in May 2016 occurred the most important flood of these last decades. Consequently, riverbanks have been harshly damaged by the water. Compared to aerial photographs, the river channel seems to have meanwhile expanded.

Figure 52: Erosion on river Kinoni

2.6.2.2 Sediment transport

In this area, sediment transport has been witnessed under its two types of carriage:

- Ø Bed load: on river Murufurwe, small boulders are carried and spread over the left bank upstream of road NR2 (due to culverts lack of capacity).
- Ø Suspended load: Kinoni River carries a lot of sand that settles when the slope decreases. This happens in the vicinity of the culvert under road NR2. Dredging is regularly performed.

Figure 53: Sediments issues on Murufurwe (left) and Kinoni (right)

2.6.2.3 Overflows

Overflows that have been located in different places and are listed below:

- On Rivers Murufurwe and Rungu, overflows progressively occur in the fields as the channel capacity decreases when going downstream.
  - Overflows from River Rungu may not return to the main channel because of seepage and terrain shape. A part of the spilled water may also transfer to Murufurwe's catchment (red arrow on map below). The river channel has been diverted south about a decade ago.
  - River Murufurwe's main overflow occur upstream of road NR2 (insufficient capacities of culverts). Water remains then between the elevated road and the volcano's slopes. According to testimonies, the road has not been overflowed. If so, it would occur in front of the school (see map below).
  - Several houses are flooded in the endorheic areas depending on the level reached by the "lake". During the site visit of August 25th 2016, local residents were seen building a new canal heading to a cave.

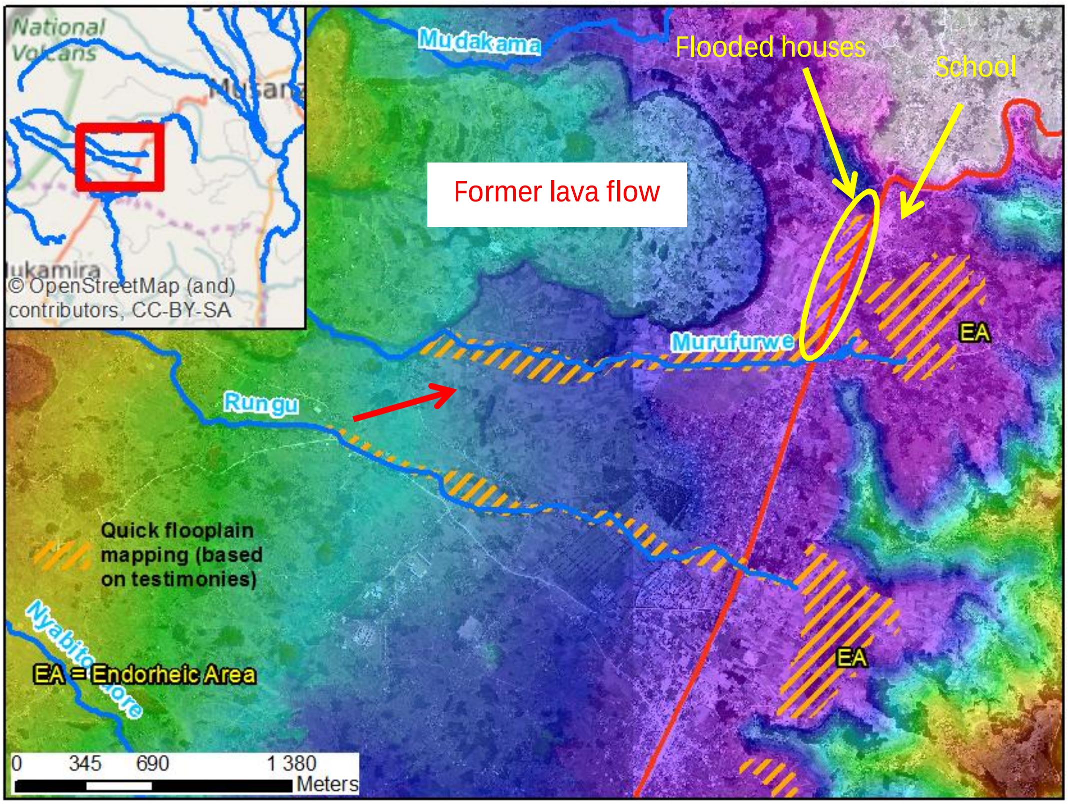


Figure 54: Location of main overflows (may 2016 flooding event) - Rivers Rungu and Murufurwe

- River Kinoni is a permanent stream likely to provide a lot of water such as the 2016 spring rain season. Water spills into the tea plantations both side of the channel. Once passed the bridge under road NR2, a part of river Kinoni is diverted according to local people's will:
  - To the eastern endorheic area;
  - To the northern endorheic area: to bring water to this area, people built a ditch with a low slope: the velocities are consequently reduced and the sediments settle and partially block the culvert under road NR2.
- Nyabitondore is a tributary of Kinoni when a flood occurs. It wasn't so some years ago because Nyabitondore used to disappear more upstream into caves.
- Next to Nyabitondore, a small gully (Ngangi) floods a neighbourhood. A house has been destroyed in 2016.

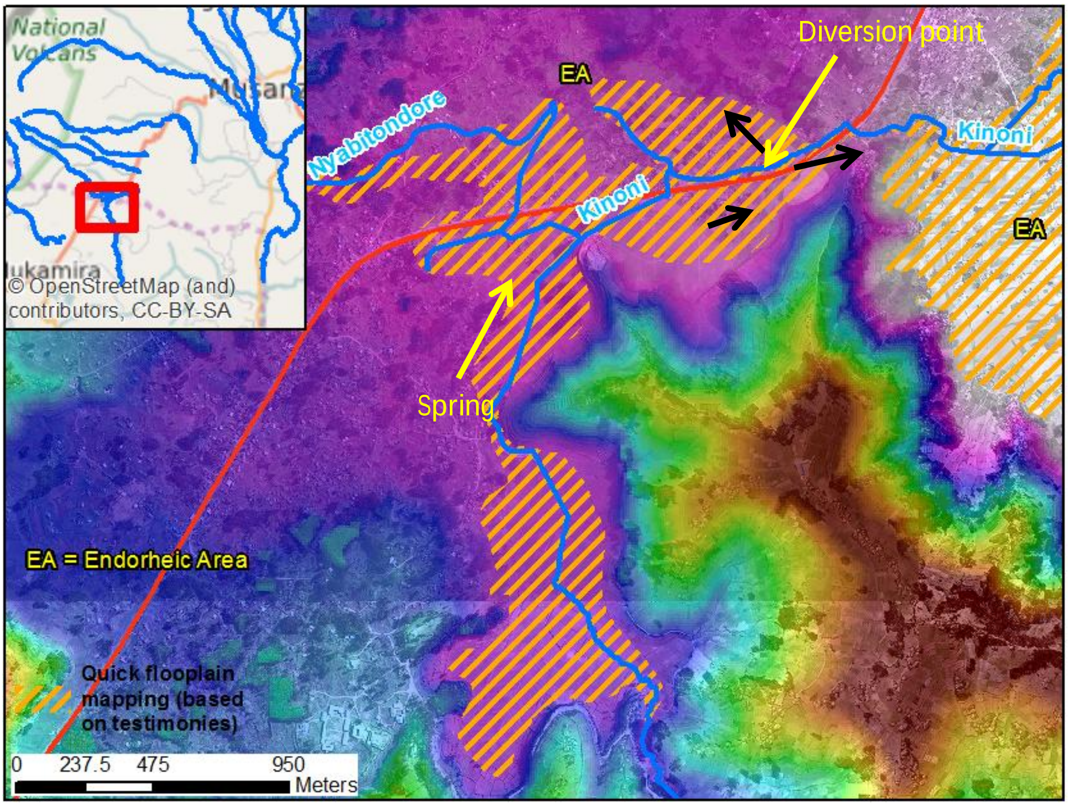


Figure 55: Location of overflows of river Kinoni and others

Figure 56: “Diversion point” on river Kinoni (May 2016)

- Bikwi River is a gully ending into an endorheic area north of the road NR2. The 2016 flooding event destroyed a dozen of houses due to long-term inundation of the lowlands (mud-made houses do not support water). If the maximum capacity of the lowland is reached, excess water may flow through a thalweg towards Kinoni River, but this scenario has never happen according to local residents.

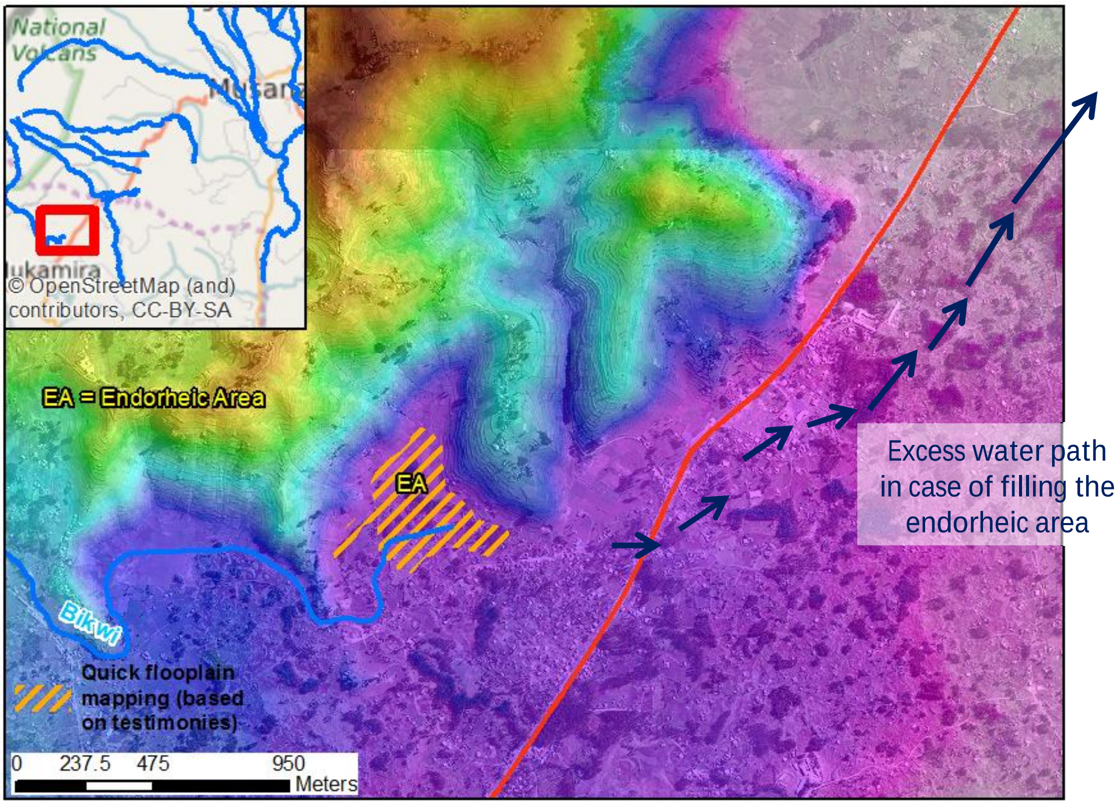


Figure 57: Flooded areas of Bikwi river

Figure 58: Wrecks of a house in the vicinity of the endorheic area - Bikwi River

2.6.2.4 Caves capacities

The endorheic areas empty with or without the help of the caves, it is just a matter of time. The following table propose to establish a “2016 state” of the infiltration capacity of the caves. This analysis is empirical and only based on testimonies or observations.

Table 3: Capacities of infiltration for some endorheic areas

Name of the endorheic area	Presence of caves	Capacity of infiltration	Duration of submersion	Evolution	comment
Mutobo right branch	yes	Good	0	Stable	Do not empty an endorheic area
Mutobo left branch	yes	Very poor	3 months	unknown	
Murufurwe upstream of the road	no	Medium	< 1 week	Stable	
Murufurwe downstream of the road	yes	Poor	?	worsening	Some caves are blocked, new others have been discovered and used for infiltration
Rungu	no	Poor	2 weeks	Stable	
Bikwi	yes	Very poor	3 months	worsening	Caves completely blocked
Kinoni (diversion to Mugogo caves)	yes	Medium		Stable	Several channels head water to different caves. Maintenance done after each rainy season (RNRA project)
Nyabitondore	no	Very poor	3 months	unknown	
Kinoni (diversion to northern caves)	yes	Medium		unknown	Several channels head water to different caves

Especially two areas are particularly worrying: Biwki and Murufuwe. On both of them, the existing caves have been blocked reducing *de facto* the capacity of infiltration. As a solution, local residents of Bikwi vicinities are planning to leave the area whereas those of Murufurwe are trying to find other caves to replace the blocked ones.

Figure 59: Bikwi lowland: years after years, sediments settle at the bottom and block the caves

2.6.2.5 Bridges capacities

The surveyed culverts under road NR2 have all been sufficient since their construction except two:

- Culvert of river Kinoni, just upstream the “diversion point”;
- Twin concrete pipes of river Murufurwe (no water on the road but large overflows in the fields, left bank)

Notice that river Rungu has overflowed road NR2, but due to remote upstream overflows.

Notice also that the bridge enabling access to the drinking water plant is overflowed almost every year.

3. Site visits – South-East river basins

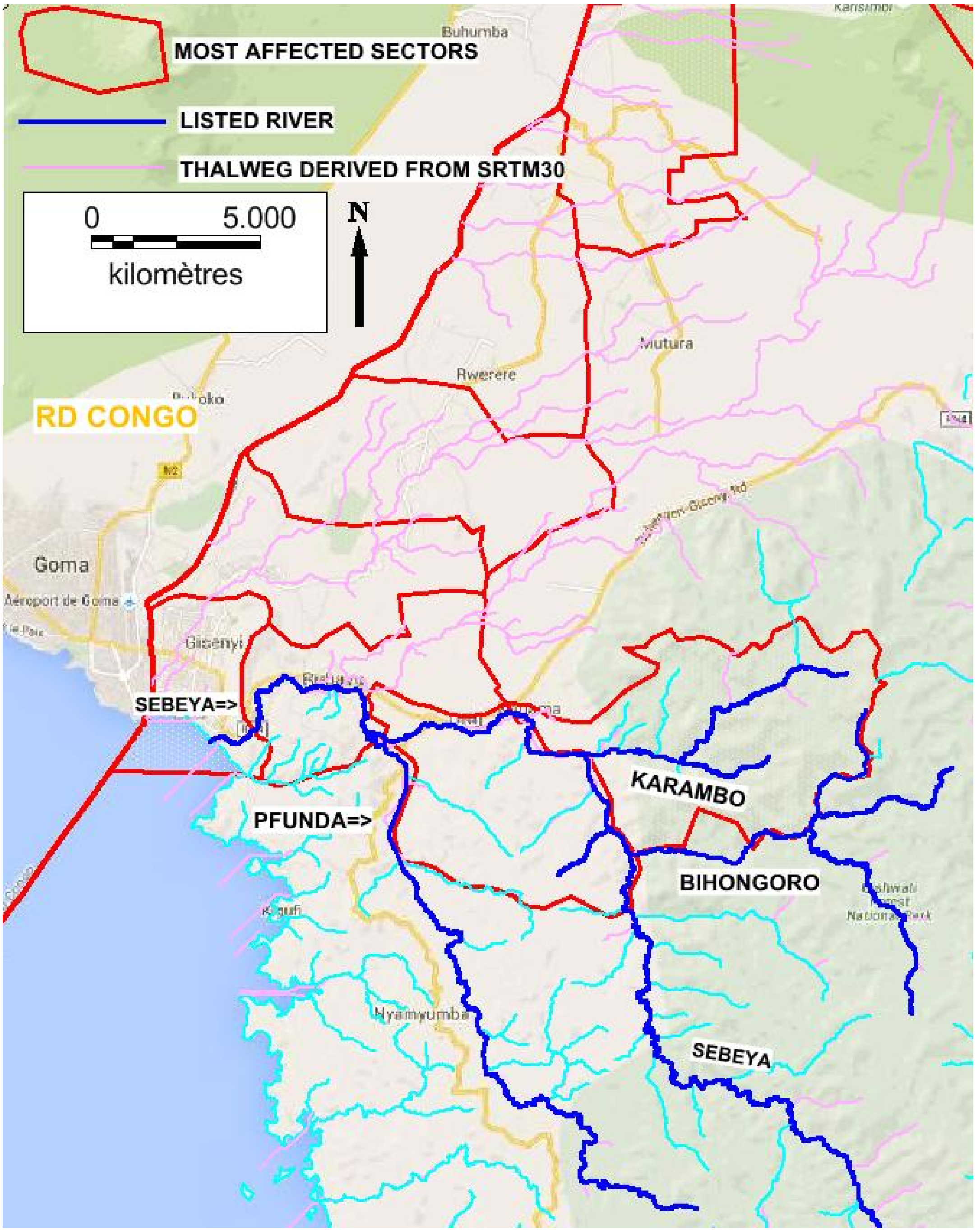


Figure 60: South East river basins' map

This chapter reports what has been seen and heard during the field visits.

3.1 Sebeya catchment

3.1.1 Description

The Sebeya catchment consists of four main rivers: Sebeya, Pfunda, Karimbo and Bihongoro. The last one has not been surveyed due to impossible access (no passable track).
These rivers are composed of sectors with low slopes (about 1%) and strong slope (more than 10%) favorable to hydropower.
Geology of catchment area consists in granite.

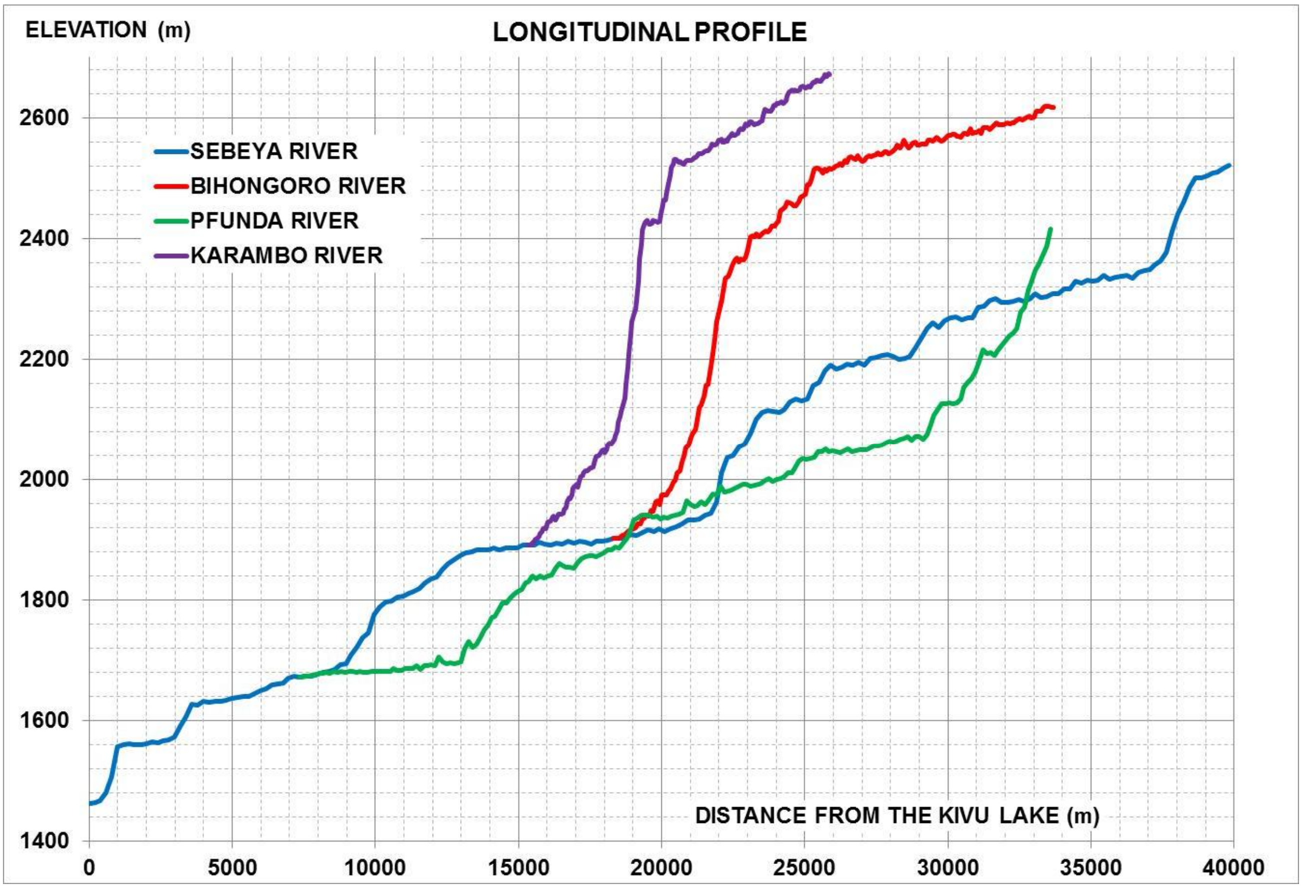


Figure 61: Longitudinal profiles of main rivers

Bihongoro and Karambo rivers have the same morphology: they consist in very steep torrents bringing river Sebeya a lot of water in a short time.

3.1.2 Raised issues

3.1.2.1 Overflows

The main issue that concerns Sebeya catchment are overflows. They are catastrophic because they occur in urban areas. Casualties were reported during the last important flooding events.
Main overflows location are listed below.

- Karambo River has devastating effects when it reaches Sebeya's floodplain. Moreover, a gully named Gisunyu strongly participates to the flooding. When both of them combine, the effects multiplied. Overflows occur on both side of the river. Beyond the right bank, a neighbourhood has been partially destroyed in 2002 and 2008 and "only" flooded in 2015. To avoid further overflows, a diversion channel has recently been dug left side (2016).

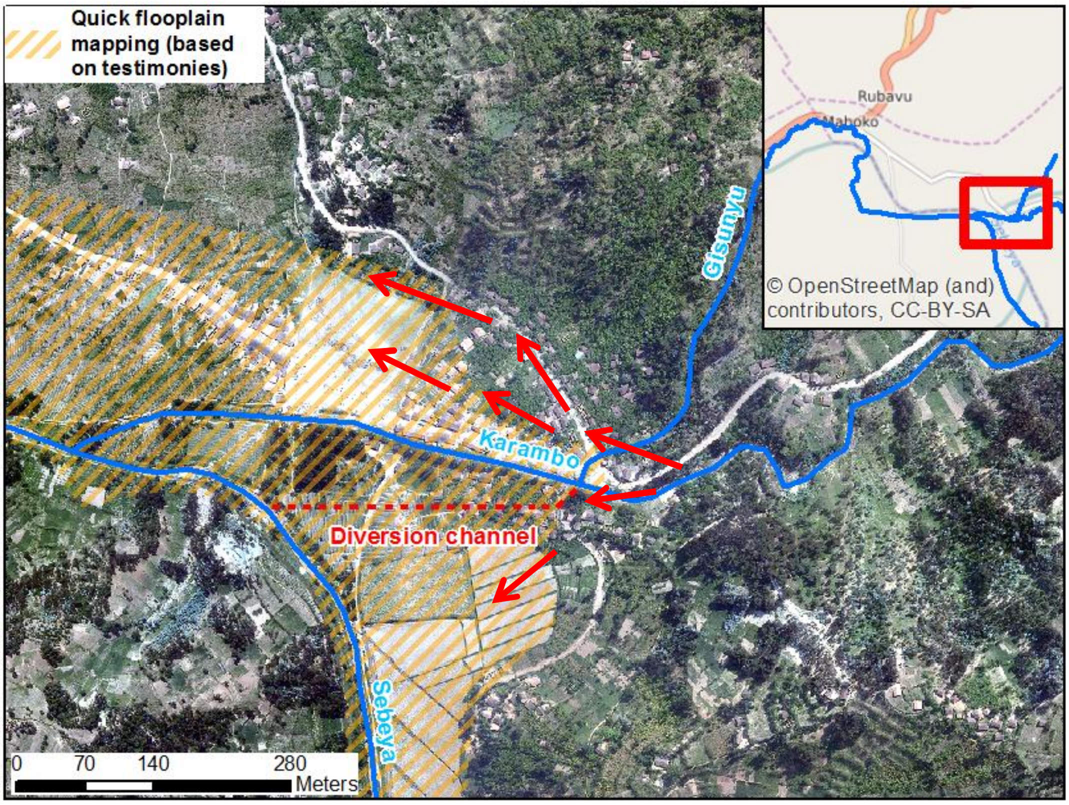


Figure 62: Location of main overflows of river Karambo, Gisunyu and Sebeya

Figure 63: Confluence of Karambo and Gisunyu (right bank): high water mark on 3rd generation houses

Figure 64: Diversion channel under construction (for excess flow from Karimo and Gisunyu rivers)

- The Town centre of Mahoko is severely flooded. It is located at a narrowing part of the Sebeya valley, just upstream of a fall. Overflows occur mainly on the left bank but also on the right bank, nearby the bridge. 2014 has been an important flooding events and some houses were destroyed.
  Spilled water on the left bank then continues downstream in a look-alike channel that ends downstream of the fall.

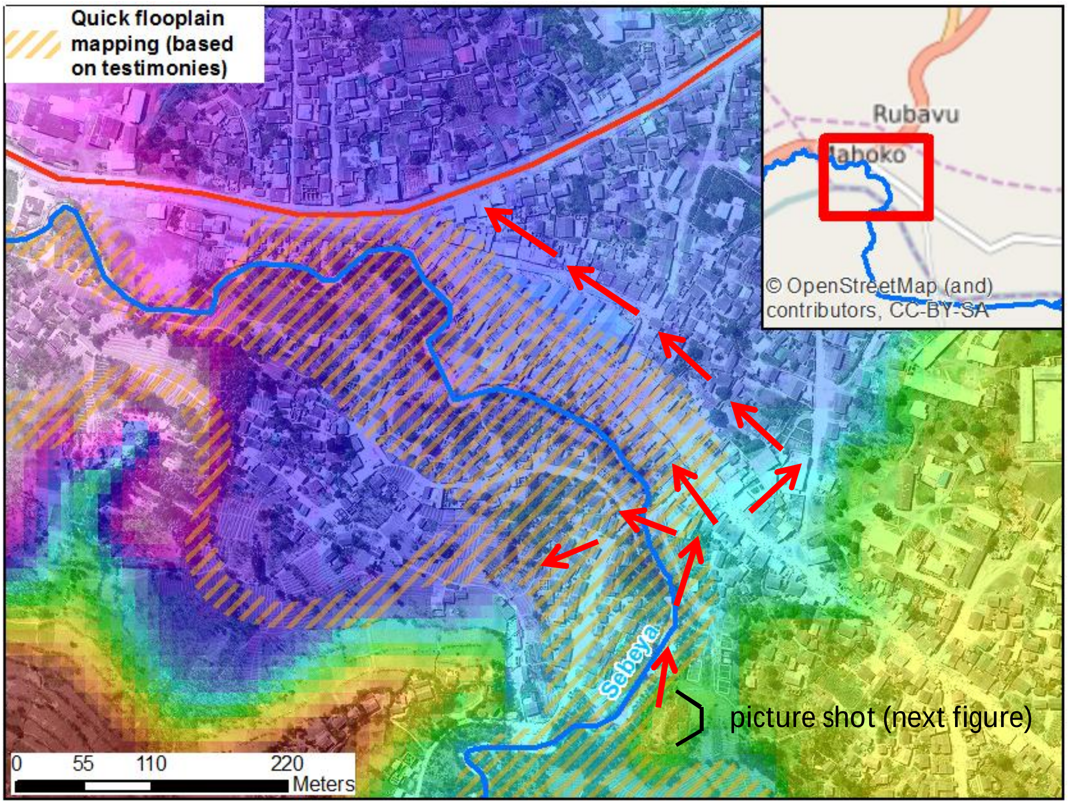


Figure 65: Location of overflows in Mahoko

Figure 66: Sebeya (looking upstream): water spills over the stone-made wall and floods

- The village of Nyundo, located downstream of Mahoko is also heavily flooded, especially the catholic school on left bank called “Petit séminaire”. Pupils and staff have been evacuated with help of the army in 2014. Water could enter through the windows (h > 1.2m).
  Right after Nyundo a new fall takes place.

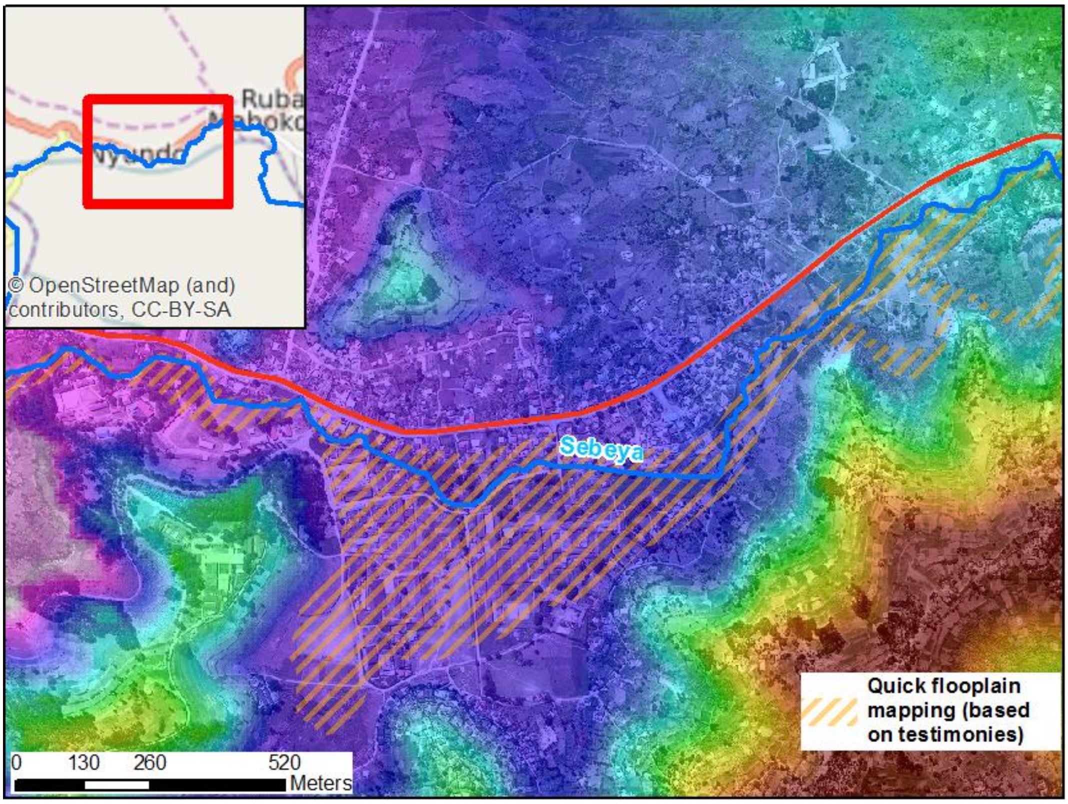


Figure 67: Approximate flood prone area for 2014 flooding event in Nyundo

Figure 68: Flooding of the school "petit séminaire"[2] (no date)

- At a place called Gihira, River Sebeya overflowed lightly in 2001 and 2008 but not in 2014. Overflows are located 500 meters upstream of an intake for hydro power.
  - Since 2008 dredging has been done in the channel.
  -

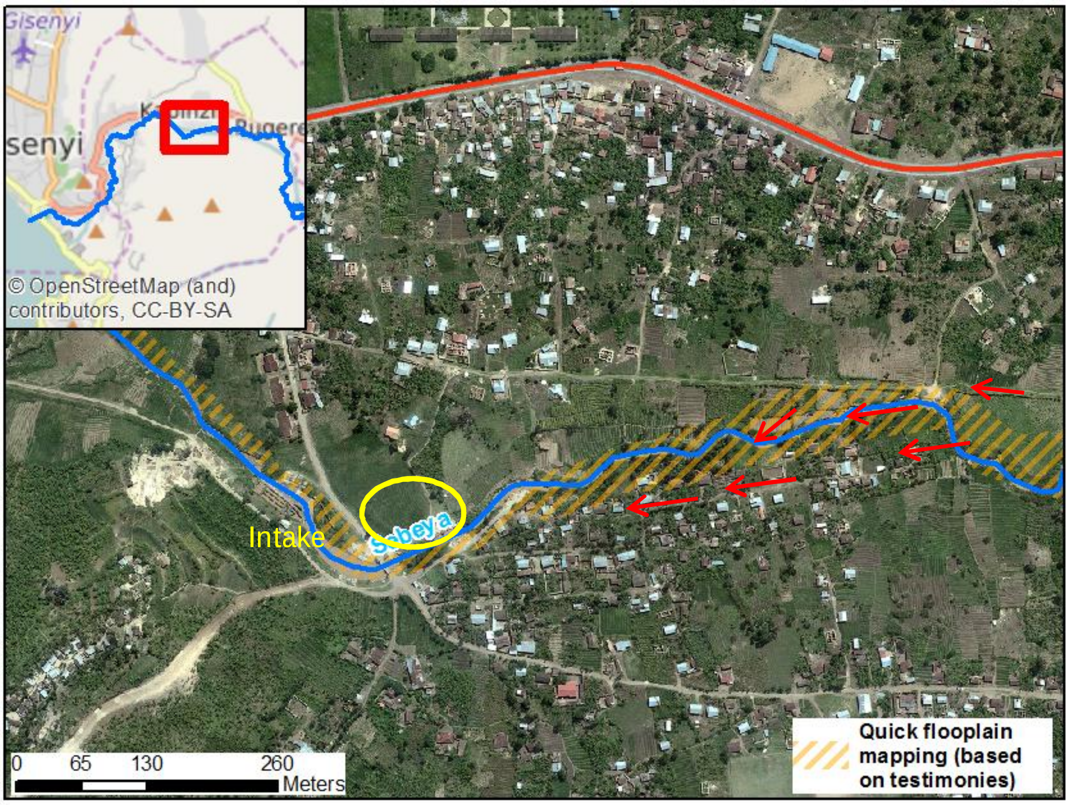


Figure 69: Location of overflows in Gihira area

[2] Picture extracted from memoir "RIVER FLOOD CONTROL MANAGEMENT: CASE STUDY OF SEBEYA RIVER" – Innoncent NDAGIJIMANA / Hertier SHUKURU – June 2015

- On river Pfunda (left bank Sebya tributary), large areas are overflowed, especially tea plantations which occupy all the flood plain. We can notice that the new road under construction which crosses river Pfunda has been built on an elevated bank. This structure will probably act like a dam because the entire width of the floodplain already used to be flooded before the new higher road and the enlargement of the bridge may not be enough (moreover, the former bridge has not been removed see picture below).

Figure 70: New bridge on river Pfunda (road to Rutsiro)

- Downstream of Gihira, river Sebeya enters Gorges and no significant overflow has been witnessed. The bridge of the coastal road of Lake Kivu has never been submerged.

Given all the previous observation, it seems that floods are particularly important in the upper catchment, less in the lower. Overflows in the large floodplains (tea plantations or, unfortunately, urban areas) are likely to reduce the peak discharge. This supposition will have to be checked with modelling.

3.1.2.2 Sediment transport

Sediment transport is an important issue on Sebeya River and is mainly caused by mining activities in the upper catchment, official as well as clandestine.
Carriage is essentially due to suspended load. Bedload carriage also occurs in steep rivers (Gisunyu, Karimbo, Bihongoro, steep Sebeya parts) but do not affect large areas.

Figure 71: Sand mining in Sebeya river

Figure 72: Suspended load in Sebeya river

3.1.2.3 Bridges capacities

Most of the bridges or culverts encountered during the field visits are overflowed or bypassed by water. Three structures have never been overflowed or bypassed according to testimonies:

- New bridge on the road to Rutsiro;
- Bridge upstream of Gihira intake (but very little clearance when a flood occurs);
- Bridge near Lake Kivu.

3.2 Thalwegs North-East of Gisenyi

3.2.1 Description

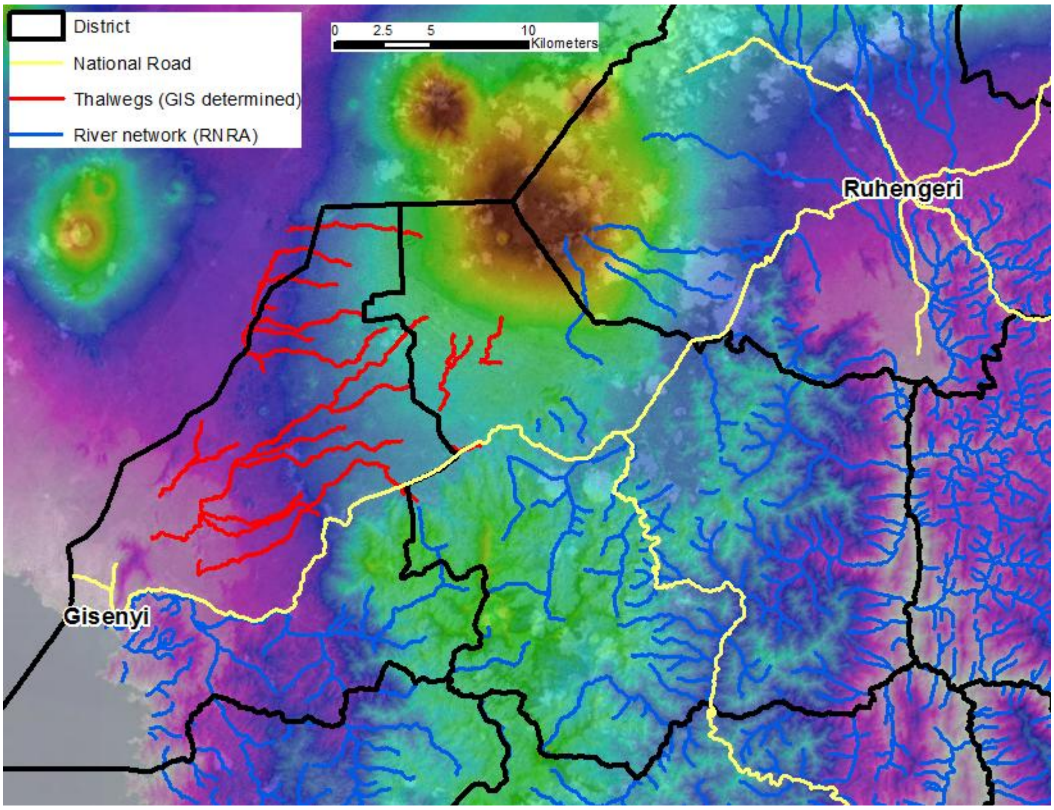
The area consisting in the sectors of Cyanyarwe, Rubavu, Bugushi and Busamana has no rivers reported in the official GIS data. Watersheds have been generated automatically to locate potential floodplains. For that purpose, a digital elevation model (dem) has been used. It is a combination of two data sources:

- the “dem10”, provided by the project, is the most accurate on the study area (cellsize = 10m);
- Shuttle radar topography mission “SRTM 30”, less accurate (cellsize = 30m). It has been used only to fill the gaps of dem10.

In the whole area, mapping the river network is very difficult for the following reasons:

- No visible channel on aerial photographs;
- Lots of places with no lateral slopes (= no deepness), hardening bed determination. The morphology is sometimes similar to an alluvial fan: water can flow indifferently into several directions.
- Presence of depressions (endorheic areas).

The map below presents the river network of the north-east area of Gisenyi.
Thalwegs have been determined with help of GIS software with the following parameters: max filled depression: 5m, drainage area = 3km², max stream length = 1km



Thalwegs have been determined with help of GIS software with the following parameters: max filled depression=5m, drainage area=3km², max stream length=1km

Figure 73: River network – Area north-east of Gisenyi

The automatically drawn thalwegs have been verified on site (displayed on GPS device). Their positions correspond to the testimonies of local residents, within a range of 50m.
Notice that the thalwegs do not reach lake Kivu because they get trapped into endorheic areas whose outlet are at least 5m above their bottom.

These thalwegs carry water twice a year, during the autumn and spring seasons. The floods dynamic is very particular on this area due to the strong permeability of the soils: when a storm (local rainfalls) strikes somewhere on a catchment area, flood propagates downstream on few kilometres before it disappears due to high seepage.
This supposition seems to fit the testimony of a local resident living at the confluence of three thalwegs: his house was essentially flooded by the water coming from a small nearby catchment (but did not mention the other thalwegs, much bigger according to their catchment).

Figure 74: Thalwegs - Lack of deepness and no channel makes them hard to locate

Due to low density of housing of the study area, few houses are flooded: just those built nearby or on thalweg axis are flooded (80cm water depth at max).
The most important flooded building is school "St Matthieu", in Busamana sector.

Figure 75: School Saint Matthieu: school's warden indicates high water mark

3.2.2 Floodplain mapping

Thalwegs will be mapped using a buffer zone of 50m on each side of the thalweg axis. Adjustments will be made on surveyed places according to observations.

4. Analysis of extreme rainfall

4.1 Data available

We arranged data of daily rainfall in the following posts and for the next durations:

Table 4: Rainfall stations analysed

RAINFALL STATION	CODE	ALTITUDE	NUMBER	BEGIN	END
BULERA LAC	40408500	1862	22	03/07/1970	17/03/1992
CYABINGO	40203500	1870	25	01/09/1969	29/11/2011
GISENYI	30304100 & 500	1550	61	27/10/1944	30/04/2016
KABATWA	30402500	2250	14	24/09/1972	24/04/1986
KINIGI	40307200	2200	44	01/11/1944	30/04/2016
KINONI	40409500	1904	29	16/12/1964	21/03/2010
KORA	30401500	2500	16	09/05/1970	18/02/1990
MUKINGO	40302500	1900	29	22/04/1958	07/09/1992
RAMBURA	30409500	2300	34	02/10/1939	13/01/1993
REMERA-RUHONDO	40301500	1900	18	08/12/1975	25/04/1993
RUHENGERI	40303100 & 500	1870	48	20/09/1952	30/04/2016
RWANKERI	30407500	2250	57	02/02/1937	30/04/2016
RWAZA	40314200	1800	60	01/11/1916	17/11/1991
TAMIRA	30302200	2300	4	15/05/1973	01/06/1980

Their position makes the object of the following figure.

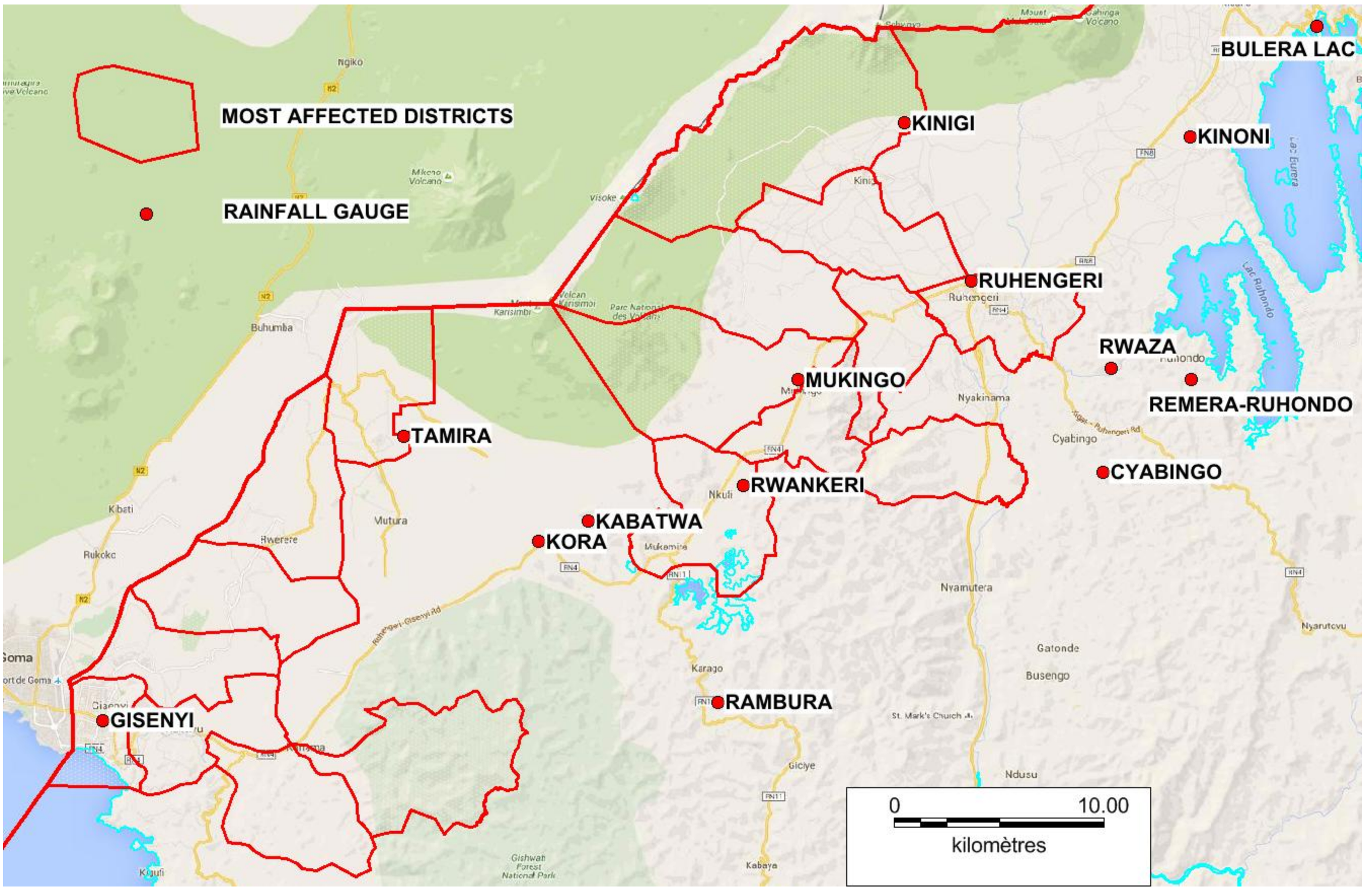


Figure 76: Situation of rainfall gauges available

4.2 Method used for rainfall's analysis

Data have been analysed thanks to a method established by ARTELIA (formerly SOGREAH) and named SPEED (French denomination) or PARDES[3] (English denomination).
The regional analysis of rainfalls forms part of this more comprehensive system named PARDES for processing mean annual rainfall and discharges as well as daily rainfall and peak flood discharges [ref.1, 2, 5].
This approach was calibrated during the early 1990s and has been validated over the past 20 years on about a hundred projects in France [ref. 6] and as many in other countries of the world.

The probabilistic hypothesis underlying this approach is based on the fact that the simple exponential decrease in rainfall observed empirically can be justified theoretically by assuming that rainfall events follow a Poisson process. In addition to enabling the rainfall frequency distributions to be determined, this theory offers a number of other highly useful properties [Ref. 4].
In this context it can hence be demonstrated that the annual maxima follow a Gumbel distribution with two parameters, one corresponding to the mean rainfall value and the other to the mean number of rainfall events (v). In practice, the fit of the rainfall observed on a Gumbel graph produces a straight line defined by Y0, the abscissa at the origin of the distribution, and Rdm, the mean value of the annual maximum daily rainfall (see following figure). Y0 is the Gumbel variable where the Gumbel straight line cuts the axis Rd = 0 (see following figure). The Poisson process theory establishes the relation v = exp (-Y0). It should be noted that the smaller the value of Y0, the greater the frequency of such events.

[3] PARDES is an acronym standing for "Probabilistic Analysis of Rainfall and Discharge for Engineering Studies”

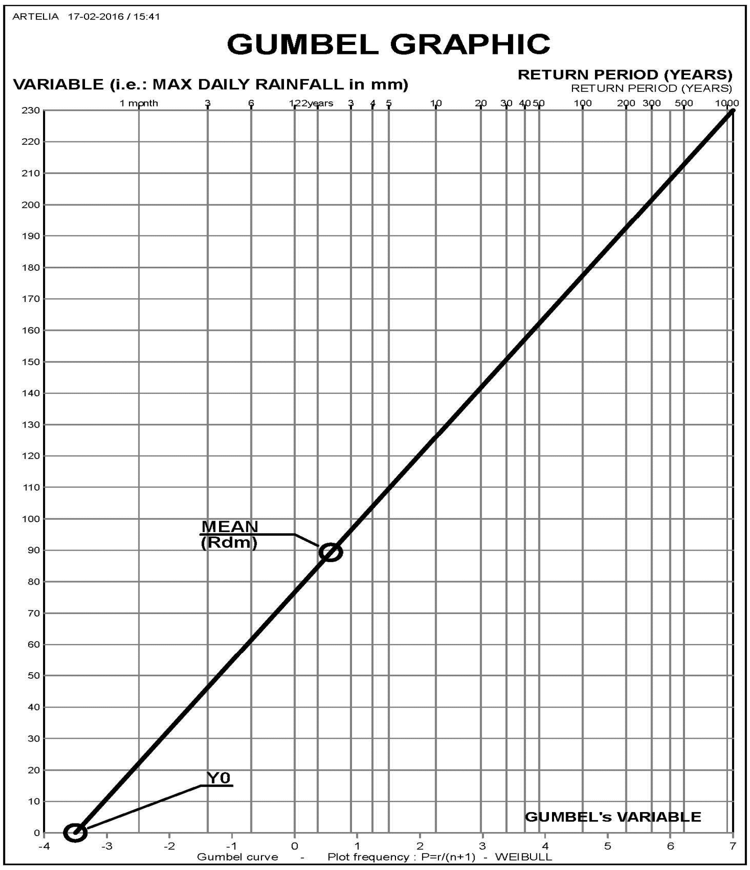


Figure 77: Gumbel graph – distribution with two parameters

From a physical point of view, rainfall events cross large territories covered by several rainfall stations. The same number of events should hence be found at these stations, meaning in practice that v is a constant for a given area which we will hence call a region and that, for this region, the parameter Y0 of the Gumbel distribution is also a constant. The rainfall regime is hence described as homogeneous.

This consequence of the theory hence makes it possible to consider a regional approach to set a regional value of Y0. All that then remains is to estimate locally the mean daily rainfall defining the slope of the straight line on the Gumbel graph (Gradex). This method offers a means of significantly reducing the sampling uncertainty on the determination of rainfall in comparison with conventional statistical methods that adjust the statistical laws to the local values from a rain gauge.

However, we have been able to observe [Ref.5] that the fits are not always straight and can take the form of a broken line due to threshold phenomena associated with orography or the presence of a cold air mass (Mesoscale Convective System (MCS) or cold air mass trapped against high ground).

Indeed, within a given region the value of Y0 is unique but the mean varies due to orographic effects: the regression lines form a beam (see illustration on figure 71). For example, rainfall is twice as heavy on a windward mountain slope as in the plain, due to the fact that each weather system is activated (the unstable air mass must rise and cool) on reaching the obstacle formed by the mountain.
However, the more the air mass is unstable the earlier it will be activated, and hence the heavier the rainfall will be. A rain gauge located in the foothills (A on the following graph) will hence receive the rainfall falling in the plain if the weather system is not very active and the rainfall from the mountainside during a major episode. In this case the regime observed will be mixed, combining light plain rainfall and heavy mountain rainfall. The parent population forms an S-shaped curve between two straight lines with the same origin: the "plain" straight line and the "mountain" straight line. We will refer to “breaks” in the fit.

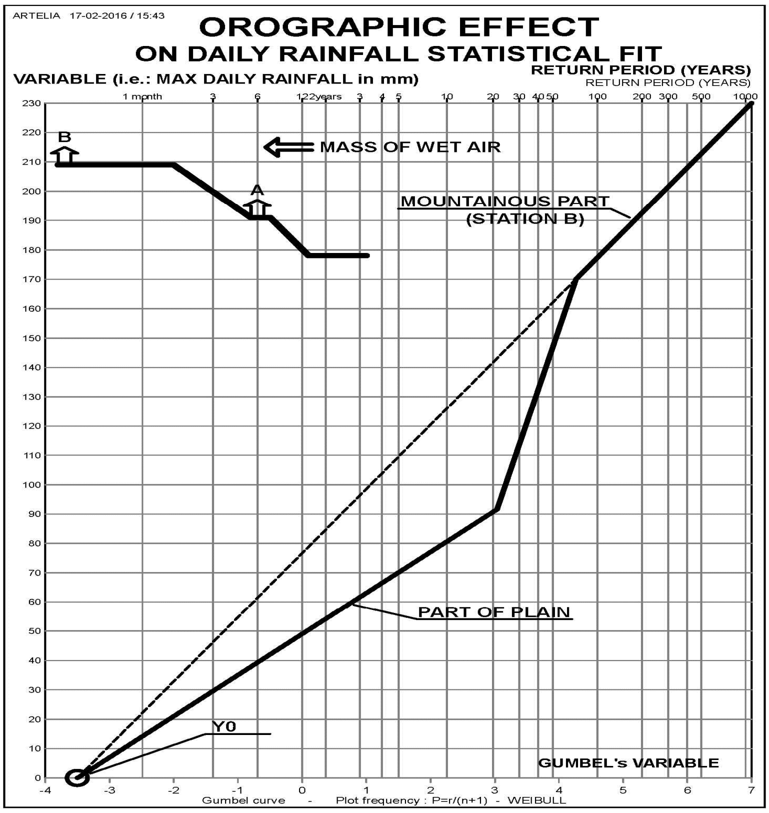


Figure 78: Orographic effect on daily rainfall statistical fit

If the rain gauge is installed quite a long way from the mountain, only exceptional episodes will be activated at this location: one or two outliers will be observed there. The same applies when the obstacle is a cold air mass stagnating here and there, being recorded randomly at different meteorological stations, or in the case of a MCS. It can be also identical with a rain gauge situated downstream the mountain.

We also demonstrate that values over threshold follow an exponential law which we can transform, by anamorphosis, into a law of Gumbel of which Gradex is the same than that of the annual maxima. It is enough for it to position the NV values superior to a threshold in the abscissa of Gumbel equal to Ln (NA / i) with i = row(rank) of the value and NA = number of years to be considered.
The exploitation of the values superior to a threshold allows determining better the pivot when the natural random sampling leads to a little bit fanciful arrangement of annual maximums (see following example).

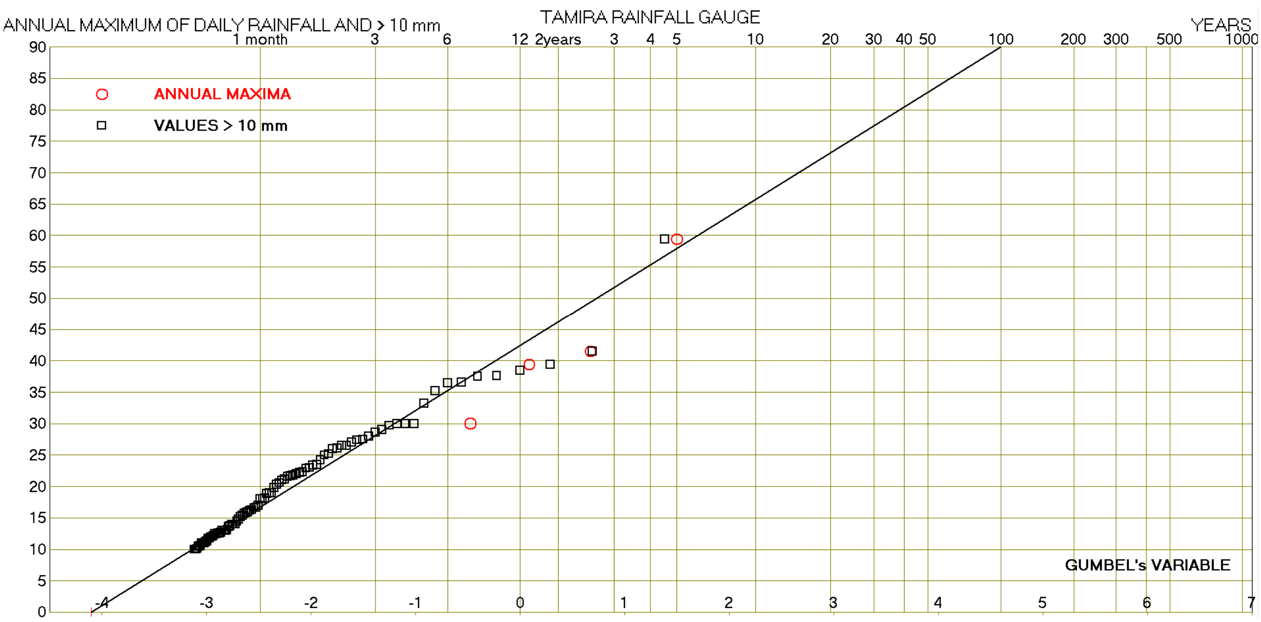


Figure 79: Usefulness of analysis of values superior to a threshold

4.3 Meteorology in Rwanda

Most of the time, the precipitation are of stormy type, due to the rise of the masses of wet air which condense at high altitude.
The most important rainfalls come from masses of wet air coming from the East, the Indian Ocean, pushed by the southern trade wind.
The most intense rains correspond to the passage of a front between a mass of dry tropical air, pushed by the boreal trade wind of the Northeast and a mass of wet tropical air, pushed by the southern trade wind coming from the Indian Ocean (monsoon).
These phenomena concern at the same time only a surface of in most 50 km² to 100 km².
That is why, very often, floods occur in places where it has not been raining, the rain being in the upper catchment.

4.4 Applications

All the series of data were analysed. We have found that the pivot'value, common to all the series, is equal to -4.1.
Each fit curve is presented in annex 4.
We have also drawn all the series on one graphic as follows (see also figure 15 in annex 4).

NOTA BENE : 2 outliers have been found at the station of Kinigi : 220 mm on June 21st 1949 and 169 mm on May 16th of 1946. As no such important value has been observed at the other stations (and June is during dry season), we have considered that they are due to mistake (decimal mistake).

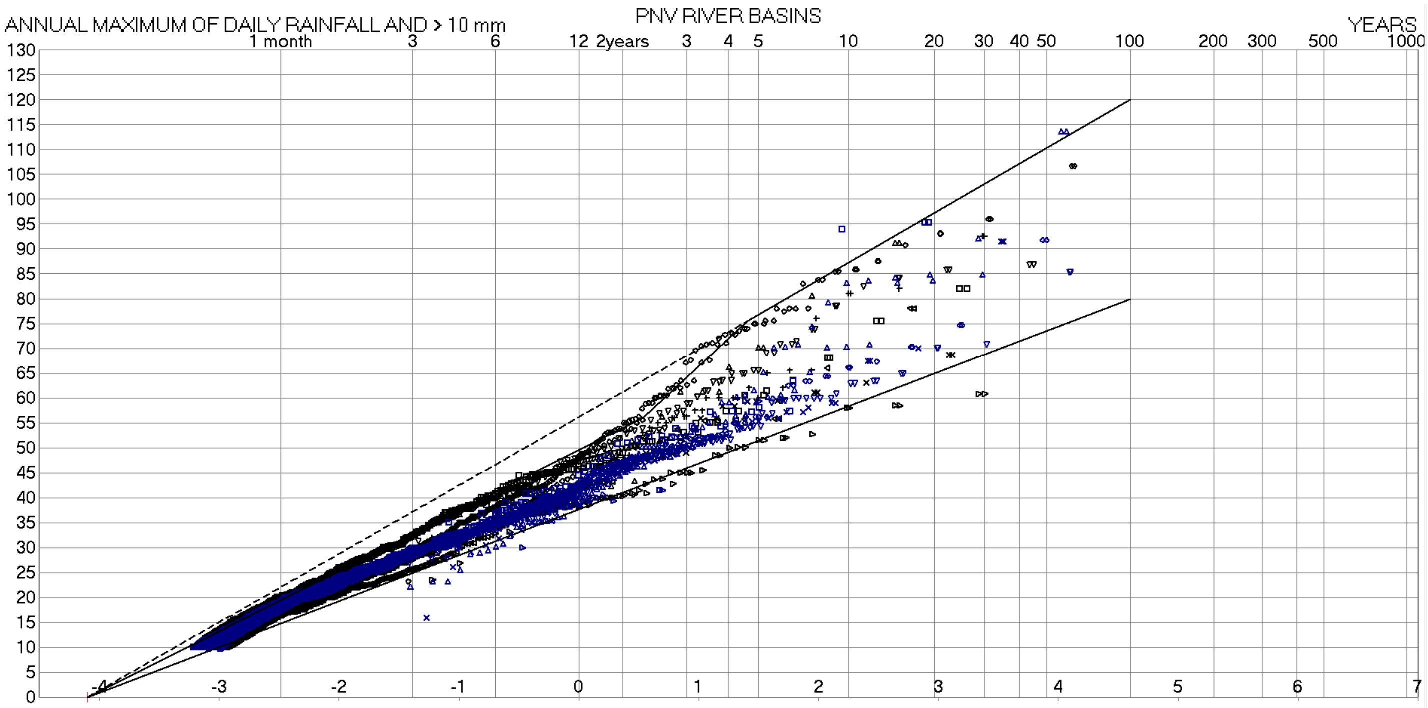


Figure 80: Rainfall's data on RNV basins

Examining the series in annex 4 shows that 5 of them present breaks. These breaks are probably due to orographic effect.
The following map shows the results in term of characteristic values of daily rainfall (see also figure 16 in annex 4).

We can see that Rd100 is between 80mm and 120 mm and Rd10, between 60mm and 90 mm.

We have analysed also the value of rainfalls at all the available stations, the day of an extreme rainfall at one particular station. This has been done for all the rainfall stations.
It shows that heavy rains fall always on a reduced area: we have never found heavy rainfall the same day on two different rain-gauges, even if they are not far from each other.
For example:

- On March 29th, 1982, it fell 95 mm of rain to Remera-Ruhondo (32 years return period) but only 47 mm to Cyabingo (1 year return period).
- On March 7th, 1982, it fell 78 mm of rain to Kora (37 years return period) and only 42 mm to Katwaba (1 year return period)
- On December 2nd, 1969, it fell 86 mm to Rwaza (6 years return period) and 28 mm to Cyabingo (much less than 1 year return period).

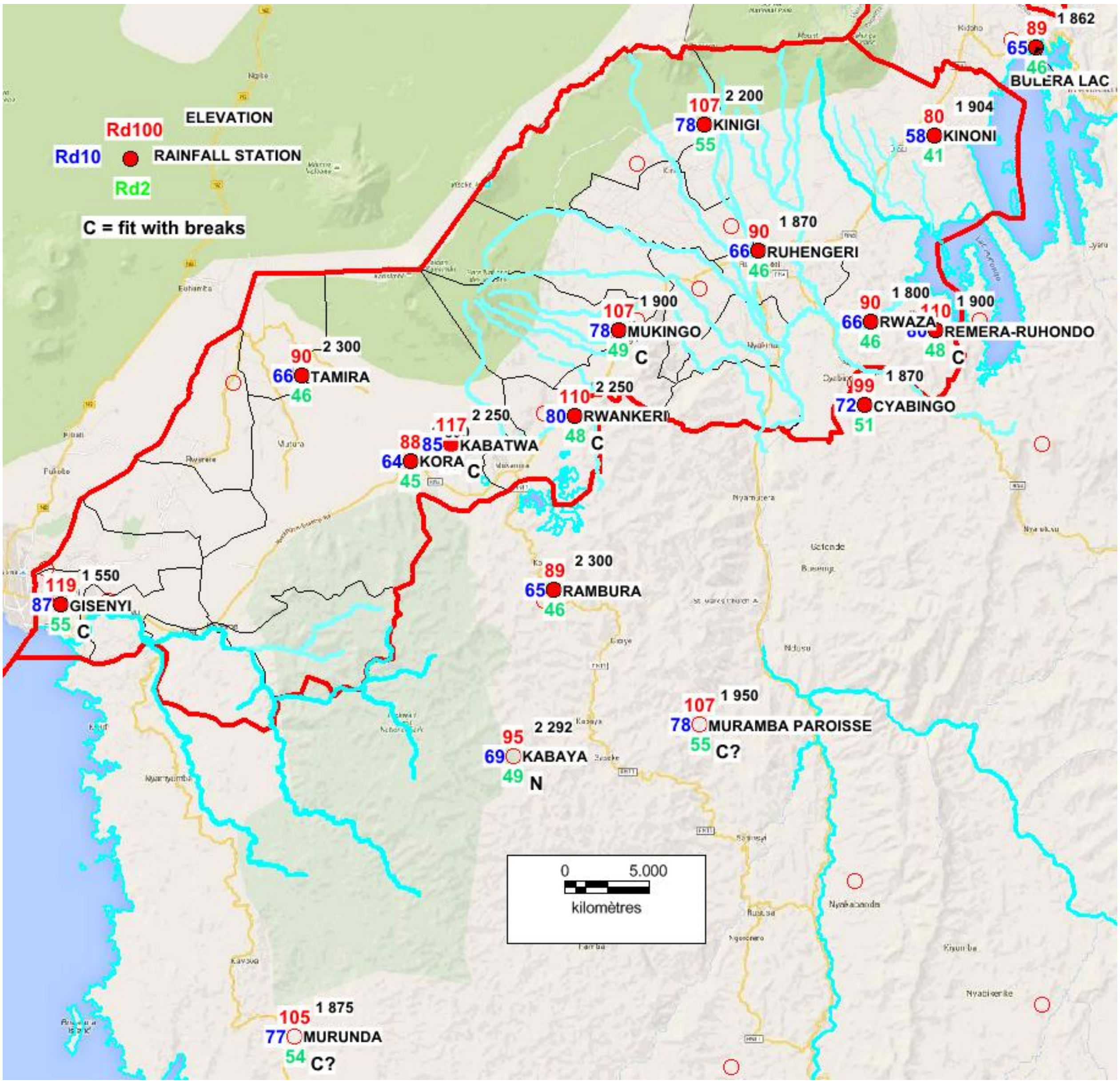


Figure 81: Map of rainfall's characteristic values

5. Hydrological study of North-eastern volcanic basins

5.1 Methodology

Analyses of previous existing reports and rainfall data have shown that:

- The precipitations are of stormy type, due to the rise of the masses of wet air which condense at high altitude.
- These phenomena concern at the same time only a surface of in most 50 km² to 100 km² (in fact probably less, according to testimonies – 30 km² ?).
- That is why, very often, floods occur in places where it has not been raining, the rain being in the upper catchment.

Due to this and to the fact that there is no data related to discharges on the small river basins of the north part of the study area, statistic method and deterministic method are not permitted. A probabilistic method is performed, different that a statistic method.

Statistic method consists in using samples of discharges values estimated at a hydrographic station, to associate an empiric value of the return period of each data (for example with the Weibull formulae), to draw all the dots of the sample on a graph and to determine the best statistic law which best fits to the sample.

As we have no data, we have use information obtained during field surveys.
Interviews of the people living near the rivers have been performed in order to know:

- What is the water height during common floods (each year or each 2 years)?
- If they have seen more important floods
- What where the stream conditions (height, velocity, direction…)?
- How long have they been there?
- Do they have seen such floods several times, with different levels?
- …

So, we have been able to associate a return period of each event, matched by an interval of uncertainty.

This interval has been estimated thanks to our experience and considering that natural hazard lead to big differences between empirical frequency and effective frequency.

For example, in France, 3 floods of river Loire have been registered between 1846 and 1866, their return period was 100 years. Considering only this period of 21 years (1846-1866), empirical return period is between 7 and 20 years. During the following period (1867, 2016), empirical return period of the highest flood is 150 years but the effective one is less than 75 years.

Measurements of the cross section at the considered places have been performed and models have been built in order to compute the discharge associated to each of these events. These values have been also determined matched by an interval of uncertainty.
For each river, we have reported all uncertainty rectangles on a graph and drawn statistic lines.

We have considered that discharges are axed on the same value of “pivot“ than rainfall or on a greater value [Ref.6 and 7].

After obtaining all the results, we have tried to find out a relation between discharge and catchment area thanks to SPEED method [Ref.6]. One of the results of SPEED method is that, on river basins which have the same characteristics (according to geology and rainfalls), discharges vary versus catchment area with the following relation:

$$Q_T = A_T \times S^{\propto}$$

This relation is, in fact, the Myers' relation.

On river basins where rainfall have cyclonic origin (high and low atmospheric pressures), it has been found that α is equal to 0.75 [Ref.6, 7].
This value is very close to what is usually considered under cyclonic phenomena. From the beginning of the XXth century, Fuller [Ref.8] proposed a formula in S^n where n was between 0,67 and 0,83 (average = 0,75). He presented other estimations from colleagues in its answer to Jarvis's article [Ref.9], all of them being close to 0.75. Also let us mention the formula CRUPEDIX French formulae with n=0,8 [Ref.10].

Considering the catchments we have studied, it appears that, even with these small catchments (< 30 km²), mostly, we were said that flood occurred without rain on the place considered but upstream. Otherwise, we can observe that the shape of the catchments are long and narrow, without big tributaries. So, we can forecast that α coefficient is probably less than 0.75.

5.2 Results

5.2.1 Kinoni River

We have got single information, from a 60 years old woman, about the biggest flood seen at the exit of the gorge (8.8 km²).
The return period adopted is between 25 and 100 years.
Discharge is estimated between 50 and 80 m^3/s.
We obtain the following graph, thinking discharges are centred as rainfalls (-4.1):

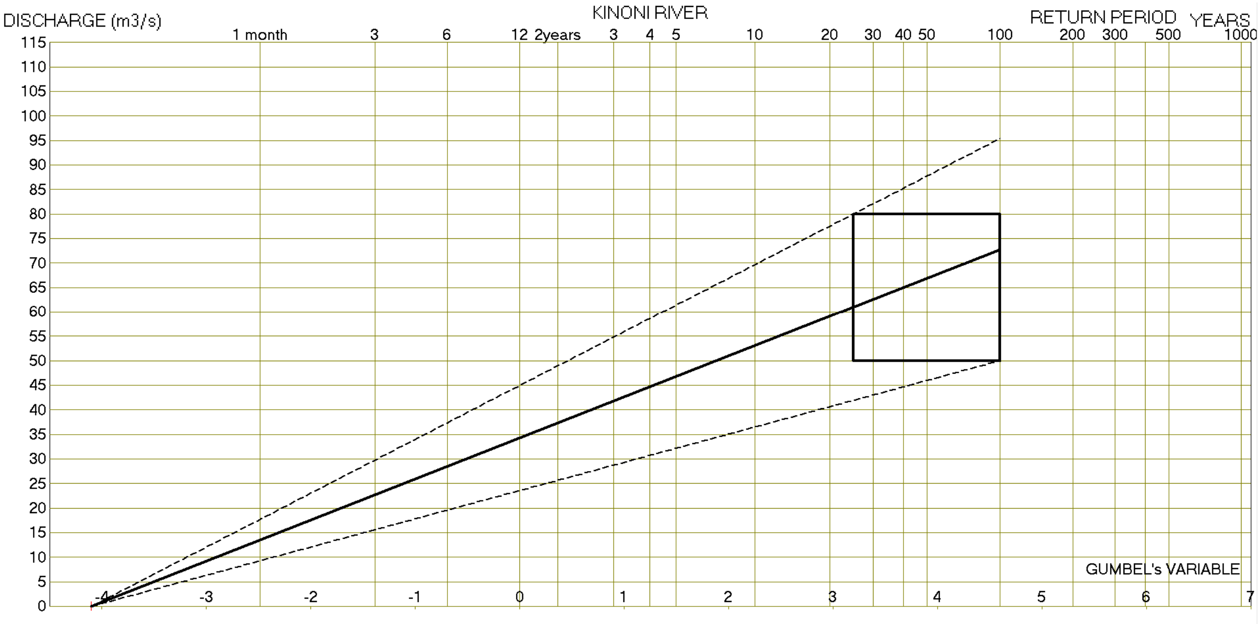


Figure 82 : Kinoni River probabilistic discharges

Mean 100 years return period value is 73 m^3/s.

5.2.2 Motogo-Mudakama and Murufurwe Rivers

Information were as follows:

- Motogo river at the drinking water plant(12.7 km²)
  - Ø 2016 flood = biggest flood since 20 to 30 years è 1 to 40 years return period
- Motogo river at the weir intake (16.6 km²)
  - Ø Thanks to overflowing all along the river between this place and the upstream one, the maximum height above the weir is about 80 cm è 2 to 5 years return period
- Murufurwe river at the overflowing place (9 km²)
  - Ø Inhabitant, present since 2008 have seen 2 overflowing in 3 years è 2 to 5 years return period

We obtain the following graph:

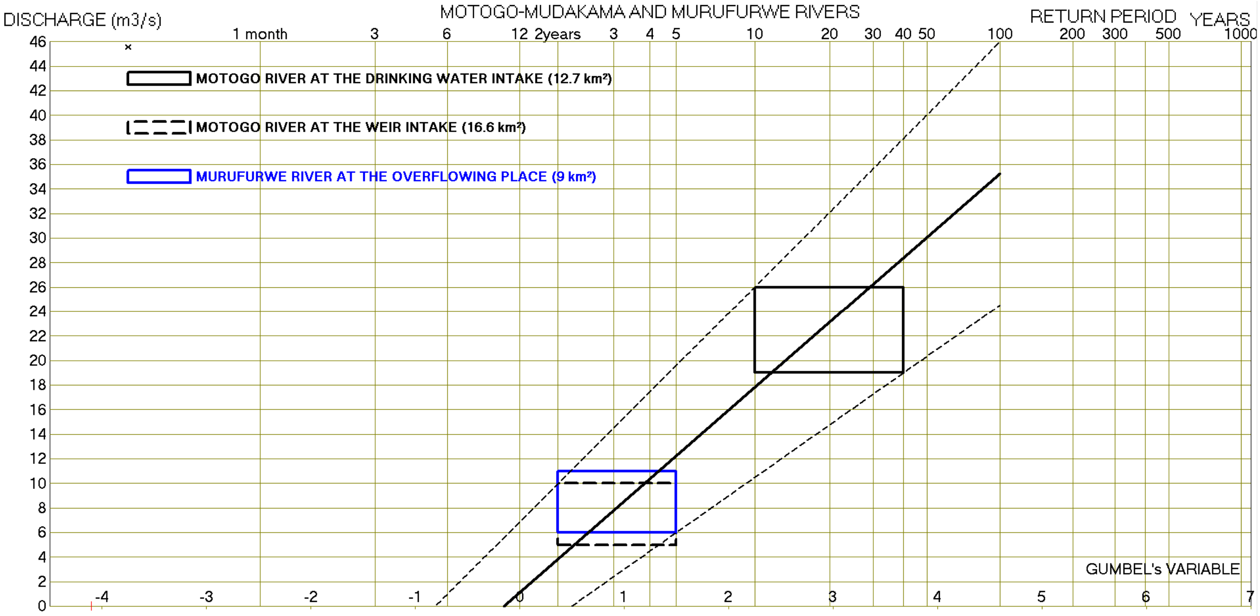


Figure 83 Motogo-Mudakama and Murufurwe Rivers probabilistic discharges

Mean 100 years return period value is 35 m^3/s.

5.2.3 Muhe River

For Muhe river at the Kinigi's bridge (15.1 km²), two events are known:

- Frequent floods
- 2014's flood which has been indicated as the biggest one by people aged less than 20 years old.

We have considered respectively the following intervals:

- 1 to 5 years
- 5 to 30 years

We obtain the following graph, thinking discharges are centred as rainfalls (-4.1):

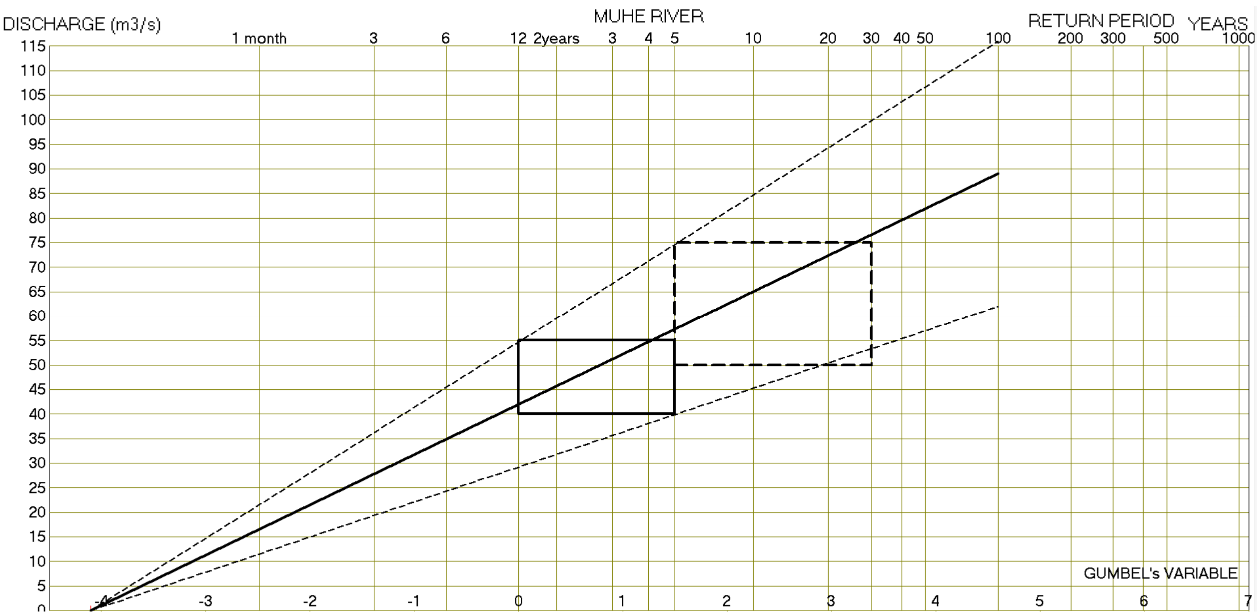


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Figure 84 : Muhe River probabilistic discharges

5.2.4 Rungu river

We obtained informations in two places:

- At the upstream bridge (5 km²), from a 56 years old woman :
  - ü Almost each year è 1 to 5 years
  - ü The maximum flood (in 2016) – It was raining at the bridge and upstream (25 to 100 years).
- At the bridge on the Gisenyi road (5.6 km²)
  - ü There has never been overflowing since 2007 (flood are almost always the same)
    - ð The capacity of the riverbed corresponds to a 1 to 5 years return period.

We obtain the following graph:

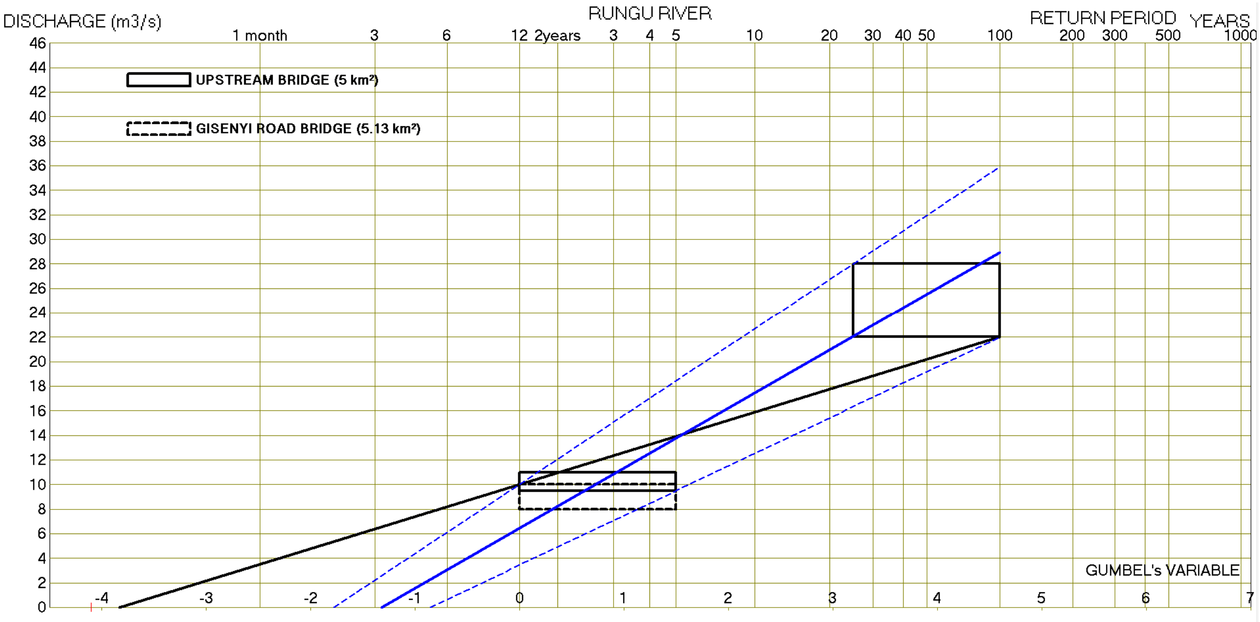


Figure 85 : Rungu River probabilistic discharges

Discharges cannot be axed on the same pivot's value. Minimum value valuable is -3.83.
The most fitting value is -1.3 that means there are initial losses.

Mean 100 years return period value is 29 m^3/s.

5.2.5 Rwebeya River

For this river a lot of information have been got but we know also that there are overflowing frequently and it is not sure that relations are effective.

- On the backside of the cycling center (5.5 km²), the level of the May 2015 flood has been reached 4 times in 9 years : è 1 to 5 years return period
- At the bridge on the Gisenyi road (31 km²), the 2014 flood (maybe 2015) is the most important flood since 15 years è 5 to 30 years return period
- Just downstream this bridge (31 km²), we have had information about frequent flood (1 to 5 years) and the highest one (2015?) è 5 to 30 years return period
- More downstream, there is a place where it overflew 3 times in 5 years (we are not sure of this information and the river bed has been modified…) è 1 to 5 years return period.

We obtain the following graph:

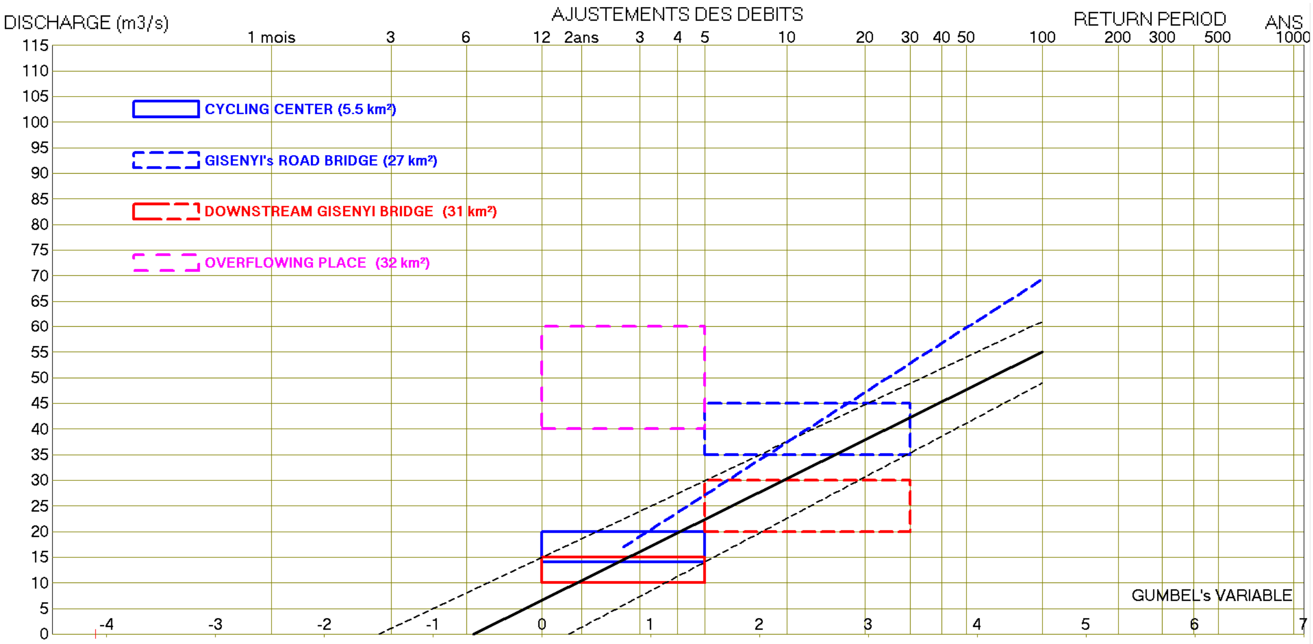


Figure 86 : Rwebeya River probabilistic discharges

It confirms incertitude on the last information.
We have drawn the mean adjustment line but we are not sure at all it fits for the cycling center dot.
That is why a blue line has been added for this place.
Mean 100 years return period value is 55 m^3/s but can be 69 m^3/s at the cycling center.

5.3 Synthesis

The following graph is a logarithm one in order to find α coefficient.

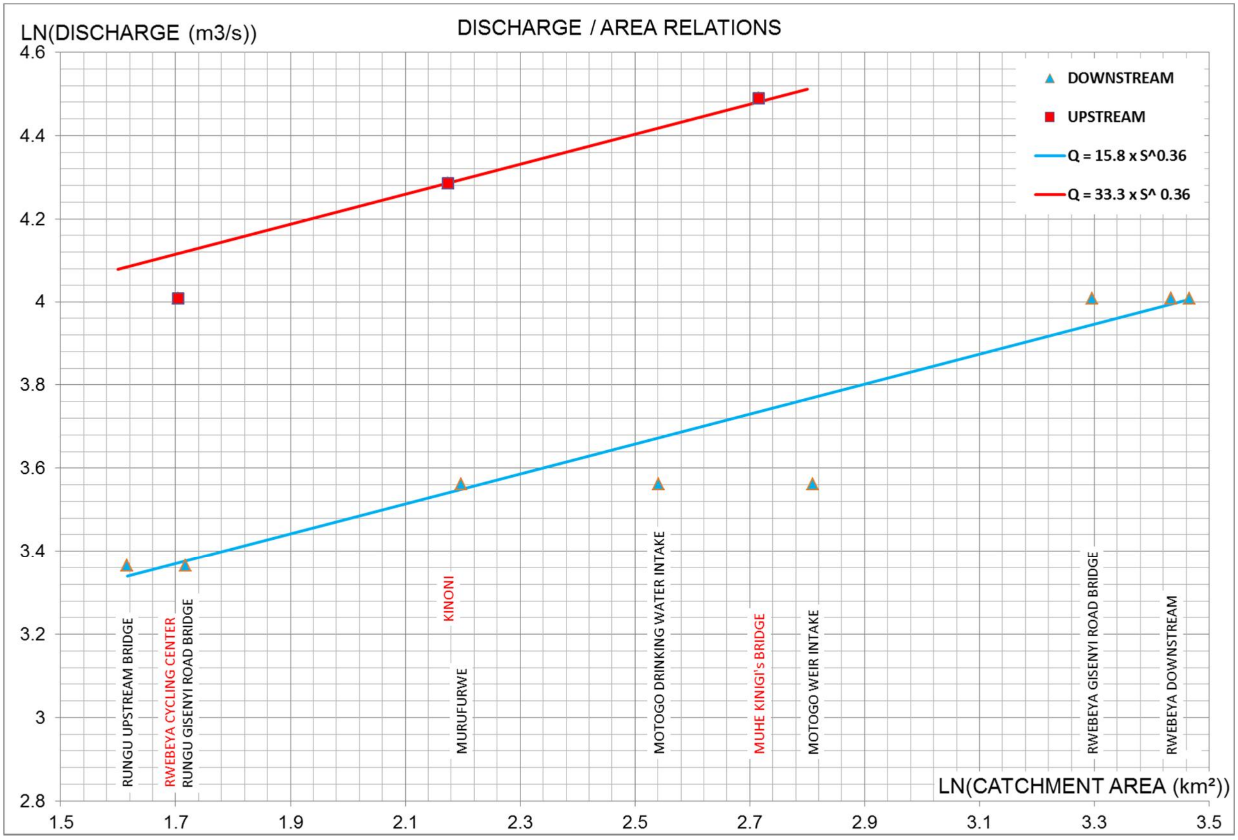


Figure 87 : Discharge versus Area relations on Noth-Eastern river basins

We can see that

- There is two different series: upstream series and downstream series.
- α coefficient is about 0.36

This value is due to the fact that rainfall does not concern the whole river basin.

We can see that it is difficult to accurately determine discharge, particularly downstream the place where there is overflowing. In that case, it is probable that a part of the water overflowing is in filtered in the ground. So the A coefficient varies gradually.

The method has permitted to have some idea about discharge evolution with catchment area. But we do consider that incertitude is very important and not consider results as absolute values.

For these same reasons (high infiltration rate) and also because of very local rainfall and because there is no data for calibration, using hydrologic model is not available with these catchments.

6. Hydrological study of Sebeya River basin

6.1 Methodology

On this catchment we will use three different methods in order to use existing data and to compare the results:

- The first method is the probabilistic method used for the North-Eastern volcanic basins.
- The second one exploits the data of height available at the river gauge of Nyundo.
- The third method consists in using hydrologic model.

We first study the site of Nyundo station in order to take advantage of the two first methods ; then the other sectors are studied. Finally, hydrologic modelling is described.

6.2 Nyundo sector

6.2.1 Probabilistic method

As for North-eastern basins, information was collected during field surveys.
Thanks to this information we have estimated the discharges.
This information is gathered in the following table.

Table 5 : Information collected on Sebaya River upstream Pfunda tributary

N°	LOCATION	Area (km²)	INFORMATION	RETURN PERIOD (years)	ESTIMATED DISCHARGE (m3/s)	
					min	max
1	Bridge upstream of Mahoko (RNRA Nyundo's station)	203	April 2015 : water up to the belt, on the floodplain. Biggest flood since 50 years	25 to 100	60	100
2	Bridge of Mahoko's village	210	Water up to the belt, on the bridge. Biggest flood since 10 years	5 to 20	40	80
3	Petit séminaire's bridge	215	1 m height on the floodplain	20 to 80	60	80
4	Bridge downstream Petit séminaire	216	1.7 m height under the bridge, each year	0.2 to 2	15	20
5		216	Water reached the road. Biggest flood since 50 years	25 to 100	60	90
6	Hydropower weir	216	80 cm above the weir in 2014	25 to 100	42	75
7	Bridge at former river gauge	217	Beginning of overflowing on the bridge	25 to 100	20	70

Stations are situated on the following map.

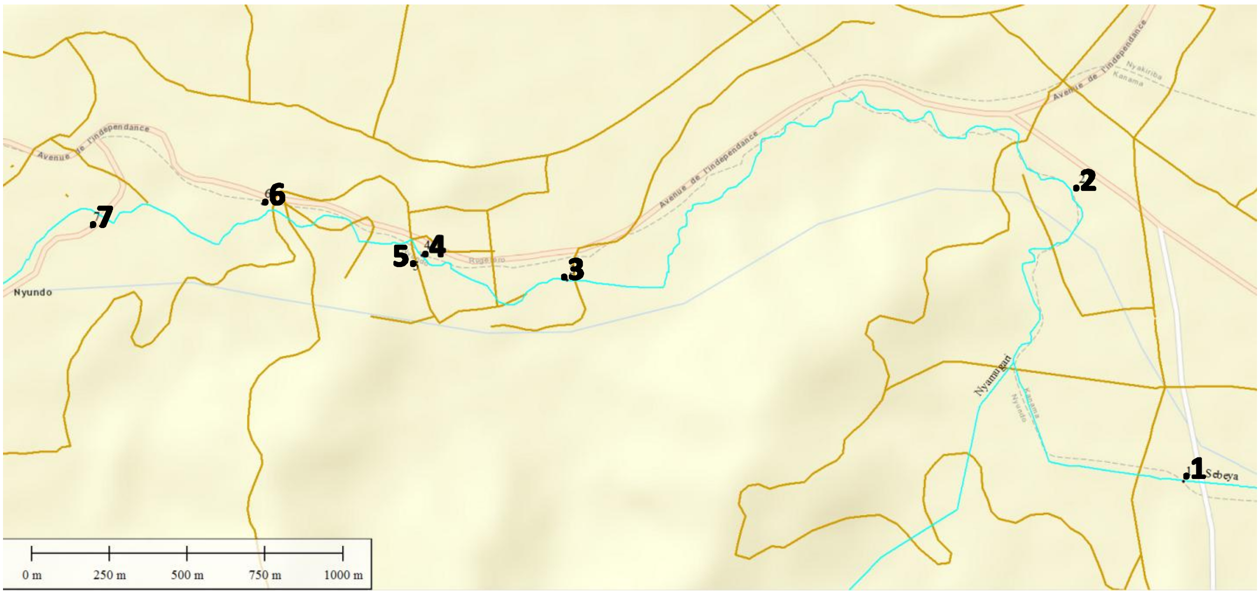


Figure 88 : Situation of information collected on Sebaya River upstream Pfunda tributary

We obtain the following graph:

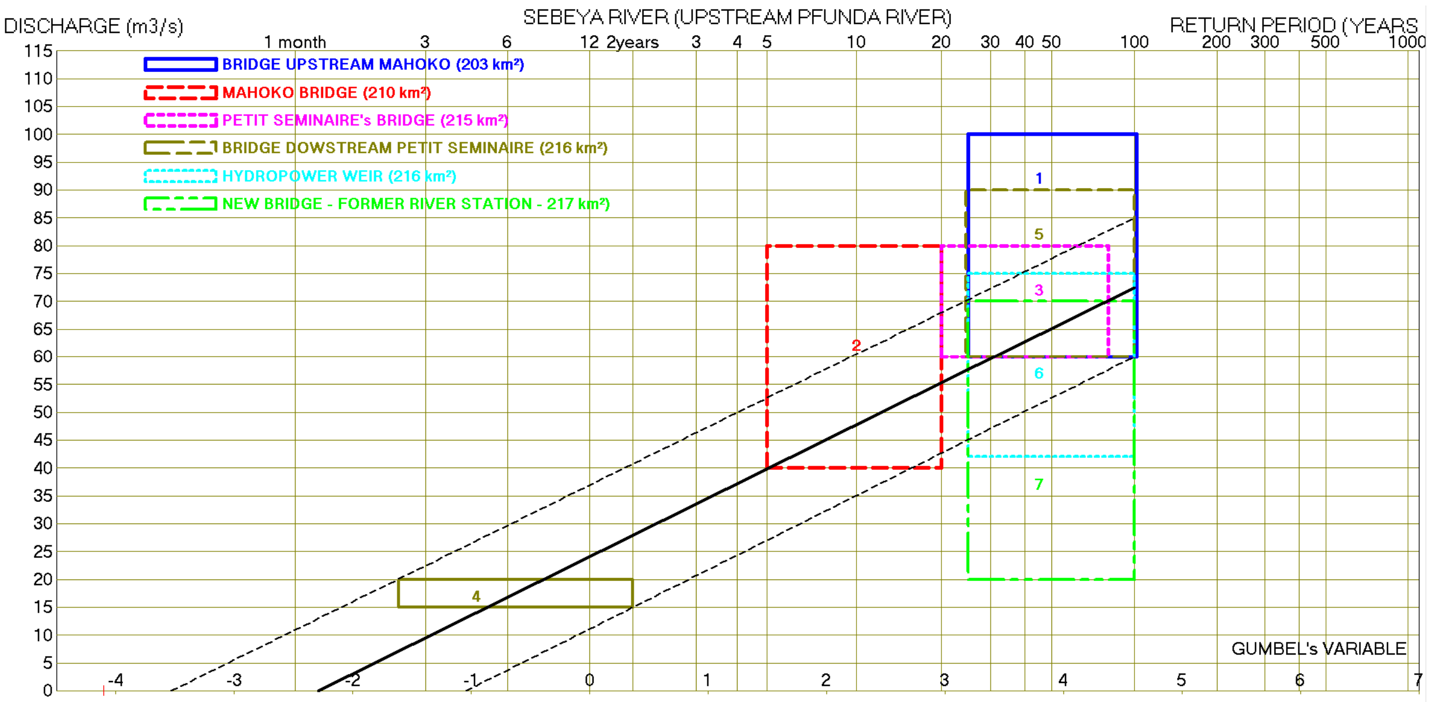


Figure 89 : Sebeya River upstream Pfunda River probabilistic discharges

Mean 100 years return period value is 72 m^3/s.

6.2.2 Statistic method

6.2.2.1 Data available

The available hydrological data consist in a time series of about 20 years of heights measured daily at the station of Nyundo, between 1974 and 2012.

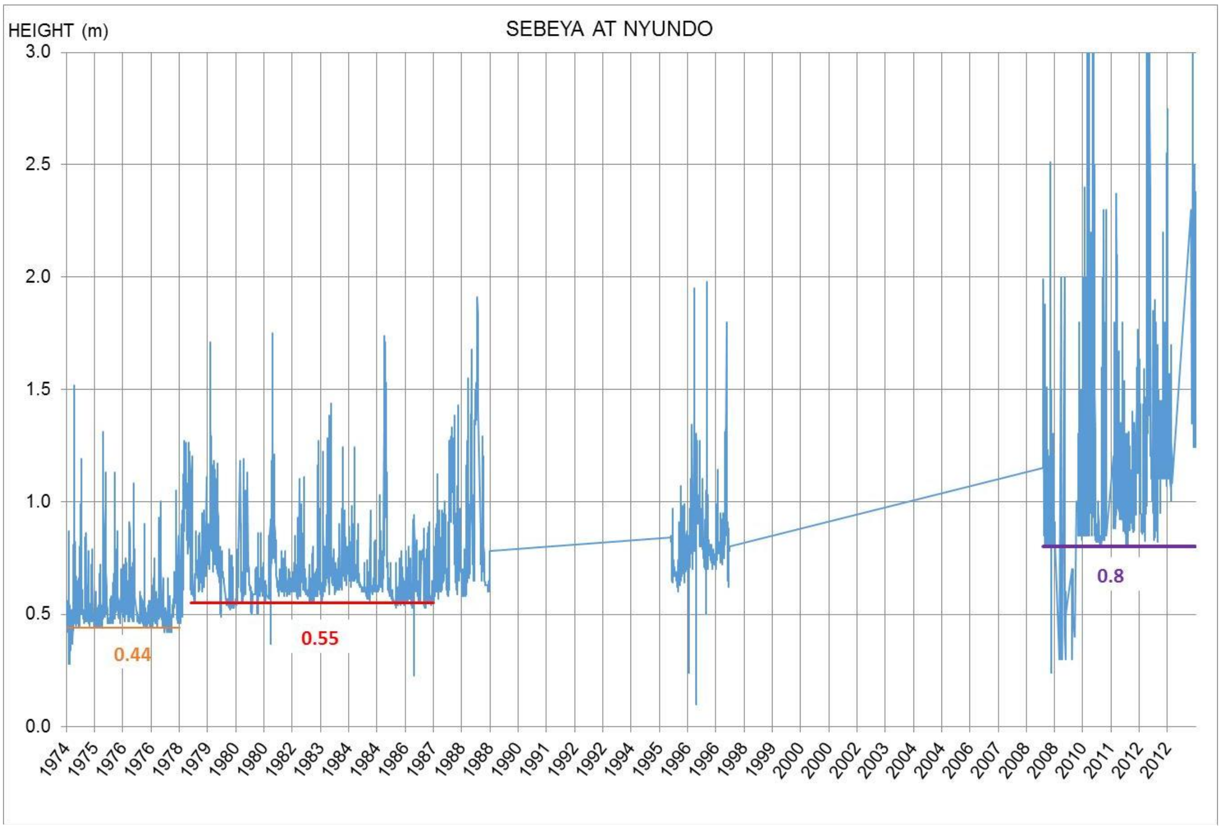


Figure 90 : Time series of heights at Nyundo station

We can see that there is some gaps from 1989 to 1996 and from 1997 to 2008.
When we study these data in detail, we can see that the minimum height varies. It seems to have increased by 11 cm suddenly in 1979 then, again, by 25 cm in 2008.
It could be due to a raising of the bottom of the bed.

6.2.2.2 Rating curves

Some measurements have been made by RNRA of the speed of the water in the cross section in order to know the discharge corresponding to a height. 48 measurements are available between 1972 and 2000.

Table 6 : Gauging of Sebeya River at Nyundo station

YEAR	FIRST	LAST	NUMBER
1972	31/10/1972	29/11/1972	2
1973	31/01/1973	22/04/1973	25
1975	15/04/1975	15/04/1975	1
1977	04/05/1977	04/05/1977	1
1980	26/08/1980	26/08/1980	1
1988	12/05/1988	11/12/1988	5
1989	11/05/1989	13/10/1989	3
1990	30/03/1990	27/12/1990	2
1992	21/02/1992	22/08/1992	4
1996	06/10/1996	13/12/1996	2
1999	17/09/1999	17/09/1999	1
2000	09/03/2000	09/03/2000	1

We have also found two other measurements made by :

- COCA Ltd on March 2014[4]
- SHER on September 2016

Ø

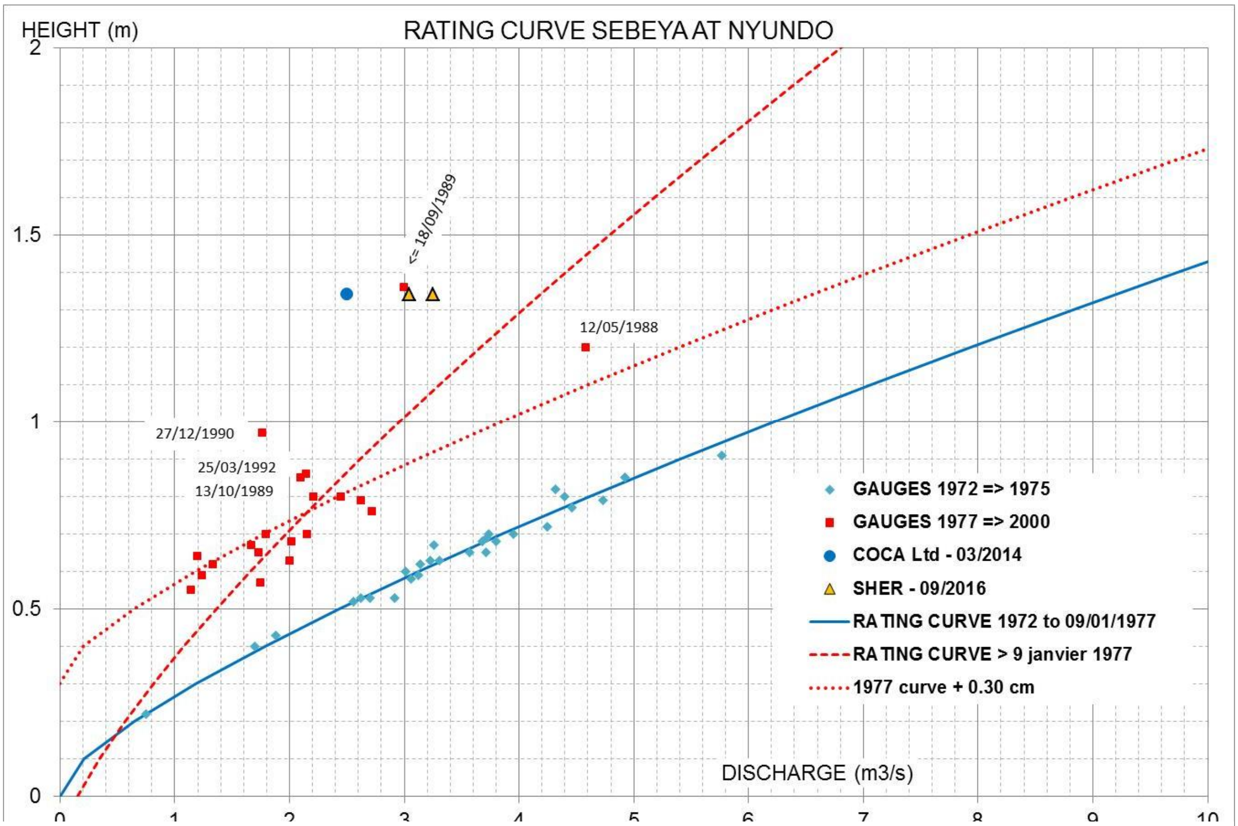


Figure 91 : Rating curve of Sebeya River at Nyundo station

It can be seen that measurements are not homogeneous:

- From 1972 to 1975, they are homogeneous and a rating curve has been defined by RNRA.
- After 1975, they are scattered and a second rating curve has been defined by RNRA but we could also consider that the river bed heightened of 30 cm.

[4] Technical studies for the designing a retention/detention pons for controlling – Final Report – October 2014 for RNRA

- The last measurements (2014, 2015) are homogeneous with the measurement dated September 1989 and could be explained by an elevation of 75 cm of the river bed since 1975

All these observations are contradictory to analyses made on the series of heights of water.

To try to find an answer to these contradictions, we built a digital model of flow. We considered two situations extreme with regard to the hypotheses of roughness :

- Ø Minimum Strickler coefficient of river bed = 18 – Maximum roughness
- Ø Minimum Strickler coefficient of floodplain = 6 to 8
- Ø Maximum Strickler coefficient = 26 – Minimum roughness
- Ø Maximum Strickler coefficient of floodplain = 10 to 12

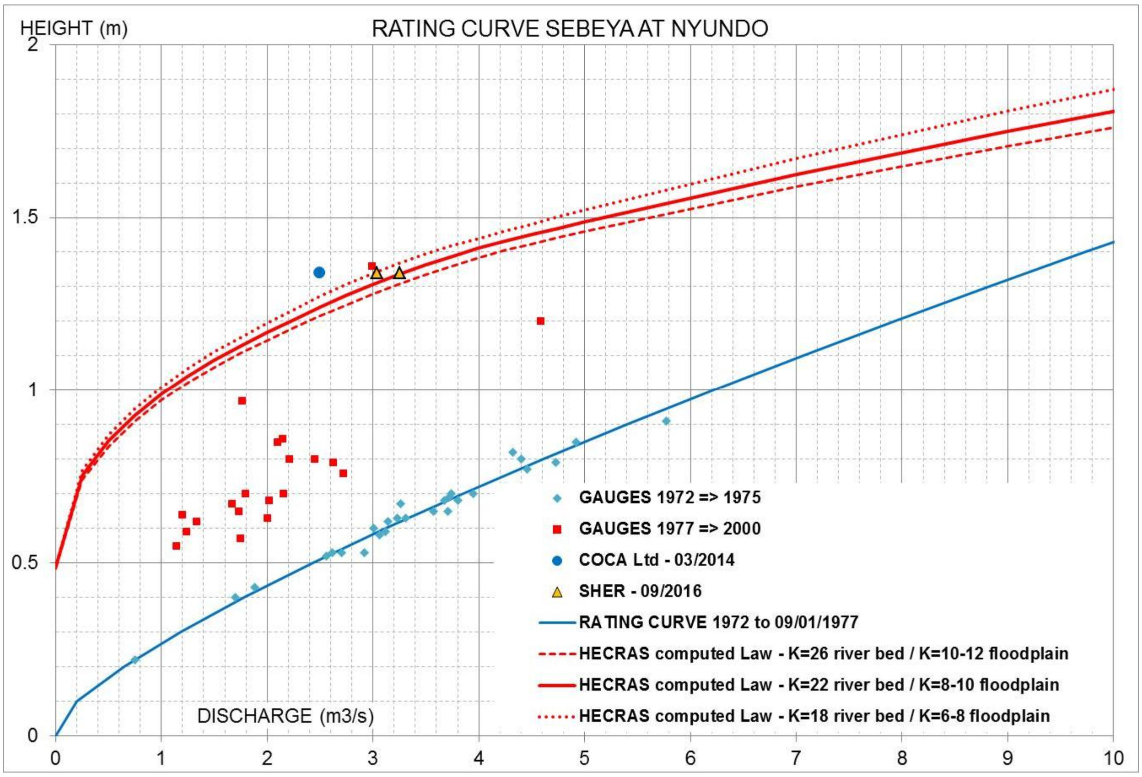


Figure 92 : Comparison between rating curve and computed laws

We can see that the relations fit with the last gauging points but not with the former data.
Rating curve established by RNRA does not take into account overflowing on the floodplain.
In order to transform heights in discharges taking into account overflowing, we have considered:

- Between 1974 and 1976, the rating curve obtained with a river bed 75 cm below present level.
- Between 1977 and 2000,three different laws :
  - o The previous rating curve (è maximum discharges) ;
  - o The rating curve obtained with a river bed 40 cm below present level (è medium discharges) ;
  - o The rating curve obtained with the present river bed and the maximum roughness (minimum discharges).

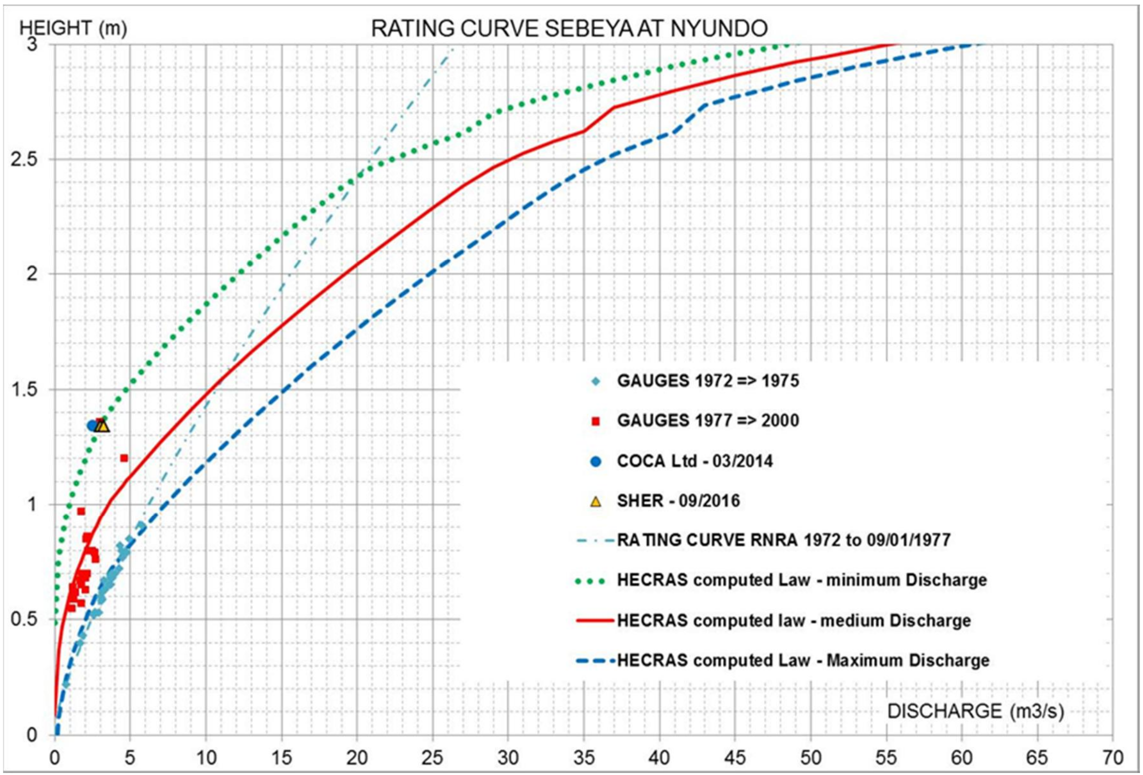


Figure 93 : Finally adopted rating curves at Nyundo station

We have used Peak Over Threshold method to analyse the discharges. We have transformed the values of height in discharge with a threshold of 1 m: all the peak heights which are more than 1 m have been considered and transformed in discharge using the three different rating curves.
It is shown that the Peak Over Threshold values follows an exponential statistic law which can be transformed in Gumbel's law by a mathematic relation.

The following figure shows the results.

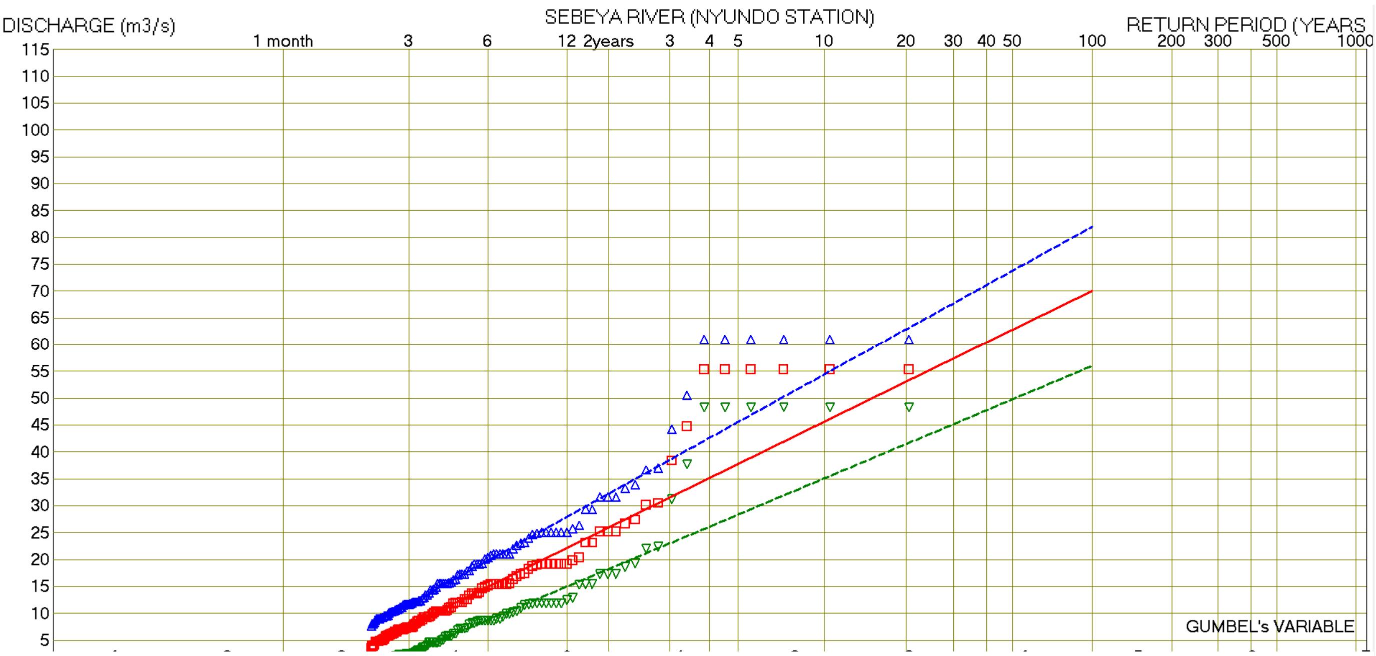


Figure 94 : Statistic analyses of Sebeya River discharges

We have been able to define three different lines which fit with the three different samples.

Extreme values are note significant because they are related to height equal to 3 m. In fact these values have not been observed but it indicates that there is overflowing without knowing the exact level.

We can compare these results with those obtained with probabilistic method:

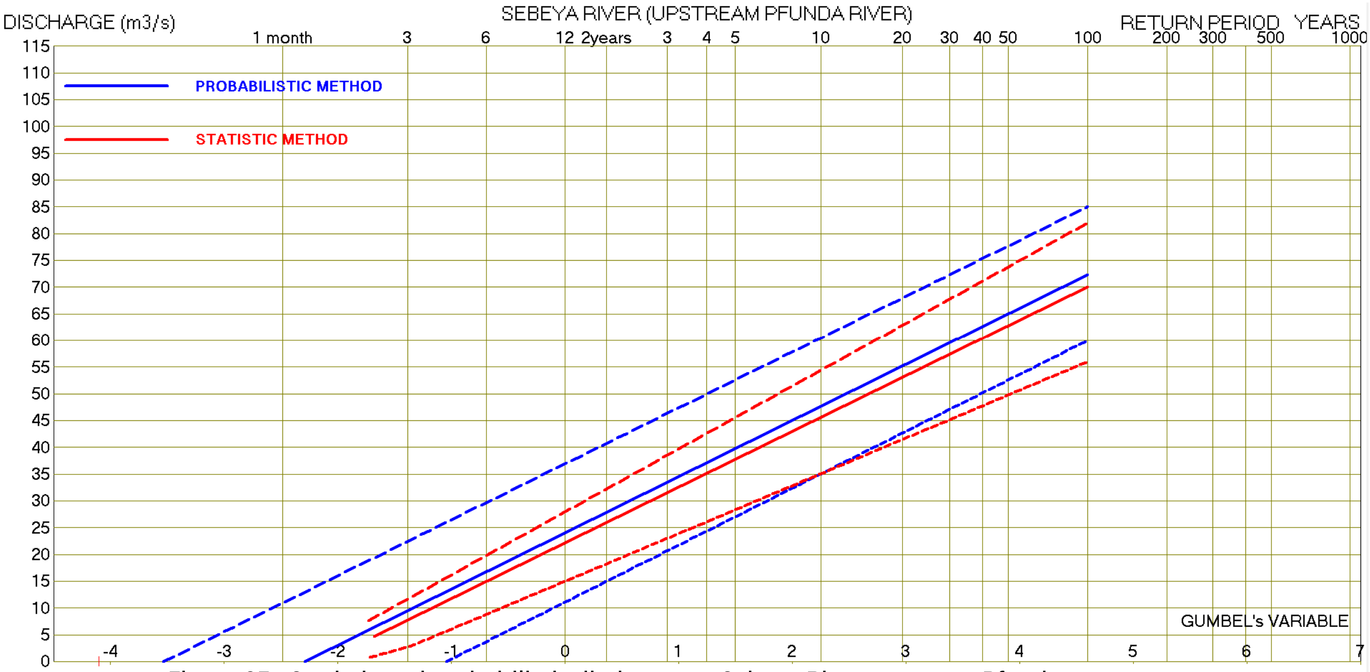


Figure 95 : Statistic and probabilistic discharge on Sebeya River upstream Pfunda

We can see that both results are completely coherent.
It means that 100 years return period discharge is about 70 to 74 m^3/s upstream Pfunda River confluence. The maximum interval of uncertainty is [60 m^3/s – 82 m^3/s]

6.3 Sebeya downstream Pfunda River

Collected information is as follows.

Table 7 : Information collected on Sebaya River downstream Pfunda tributary

N°	LOCATION	Area (km²)	INFORMATION	RETURN PERIOD (years)	ESTIMATED DISCHARGE (m3/s)	
					min	max
8	Bridge upstream Gihira intake	358		0.2 to 2	22	30
9			same event in 2005 or 2006	2 to 20	38	48
10	Weir Gihira intake	359	1 m height on the floodplain	0.3 to 3	40	60
11	Bridge downstream Gihira intake	361	Each year : 2.2 m height above the bridge	0.5 to 3	30	40
12			Severe flood in 2000 or 2001. Overflowing on floodplain	7 to 60	80	90

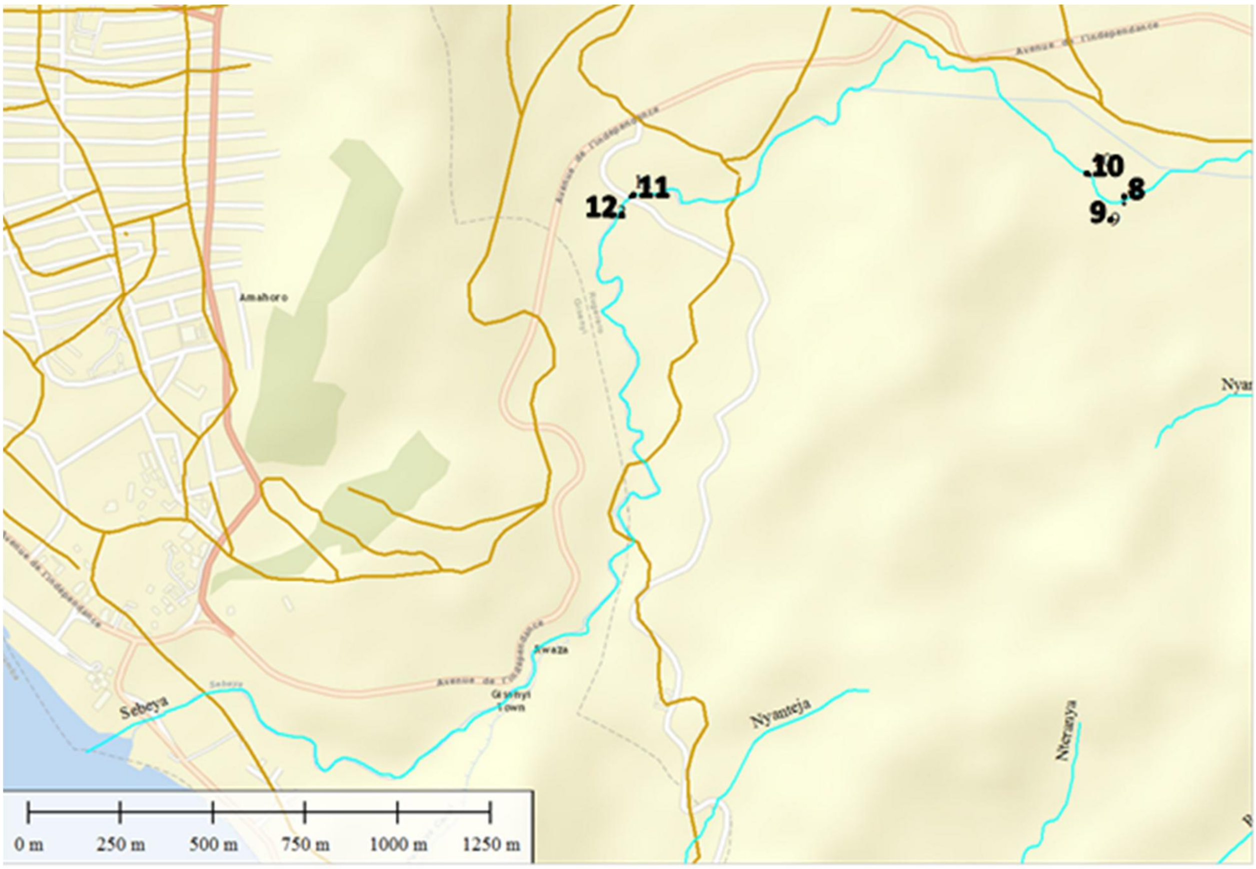


Figure 97: Locations of discharge observations on Sebeya river

In order to guide drawing of extreme lines, we have considered that α coefficient value (cf § 3.2) on this catchment is probably between 0.6 and 0.15, this last value being obtained for big catchment area as it has been shown with the studies performed in 1992 for the three dams[5]. So limits of 100 return period discharge at this location (360 km²) can be deduced from Nyundo station (~210 km²), considering that Q100 is about 74 $m^3/s \pm 10 m^3/s$.

We obtain:

		α value	
		0.6	0.15
	Nyundo (210 km²)	Gihira (360 km²)	
Min	64	88.4	69.4
Max	84	116.1	91.1

It means that Q100 is between 69 and 116 m^3/s.

So, we obtain the following figure.

[5] SOGREAH (1992). "Etude de faisabilité des 3 aménagements hydroélectriques de Nyabarongo, Rusumo-Rugezi et Akanyaru" pour le compte.du ministère des travaux publics, de l'énergie et de l'eau. Rapports 401490 de juin 1992.

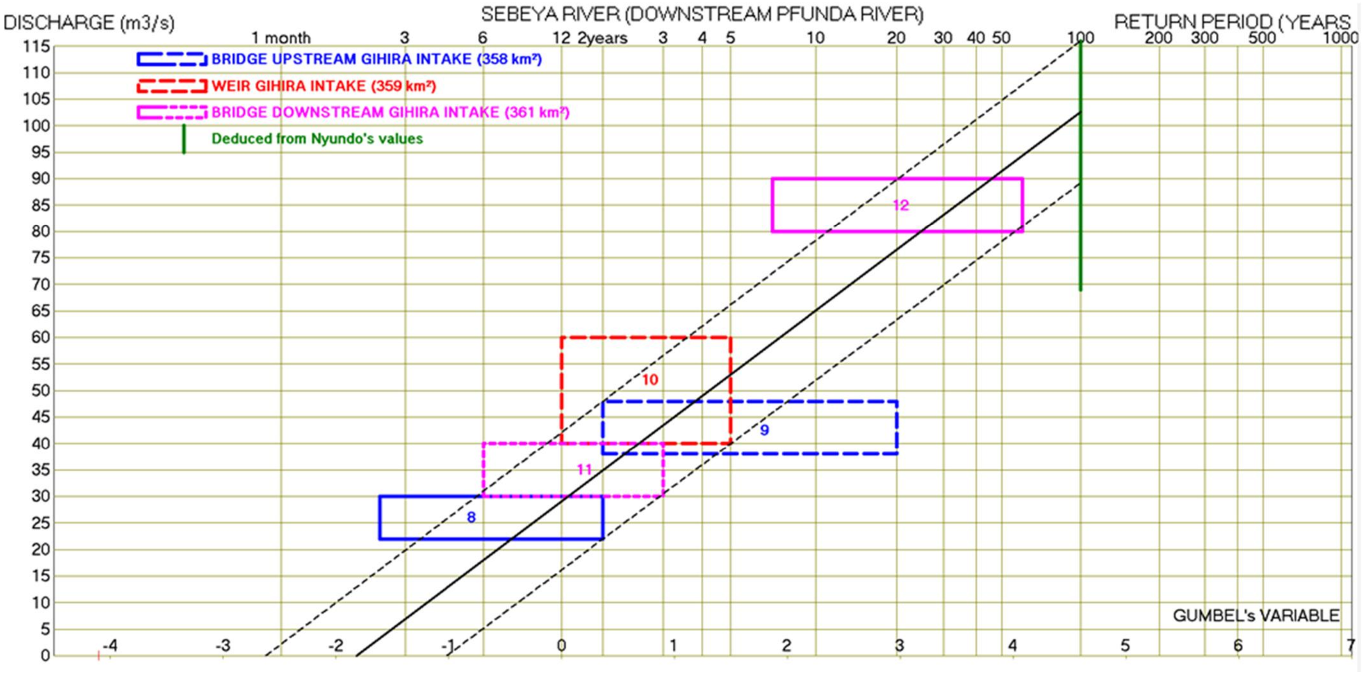


Figure 98 : Sebeya River downstream Pfunda River probabilistic discharges

Mean 100 years return period value is 103 m^3/s.

Between upstream and downstream Pfunda River, the relation between surface (S) and discharge (Q100) is finally approximatively:

$$Q100 = 2.9\, S^{0.6}$$

6.4 Hydrologic modelling

6.4.1 Tool

Following the demand of the Rwanda National Ressource Authority (RNRA), a hydrologic numeric model has been built involving the SCS runoff curve number methodology.
The free software HEC-HMS has been used. It can be found at the web page below:
http://www.hec.usace.army.mil/software/hec-hms/

A detailed description of the HEC-HMS system is provided in the technical reference manual edited by Feldman (2000).

6.4.2 Location of the study area

The model has been built in the upper Sebeya catchment area, upstream of Mahoko gauging station. At this station, the 100y return period flood is estimated at **more or less 72 m^3/s**. Heights measured have been recomputed with a new and more realistic rating curve.

Figure 99 HEC-HMS upper Sebya catchment hydrologic model

Four sub-catchments have been modelled (from north to south):

1. Gisunyu (2.3 km²)
2. Karambo (33km²)
3. Bihongoro (42 km²)
4. Sebeya (113 km²)

The intermediate sub-catchment (between other catchments outlets and Mahoko station) has not been modeled because not really participating to floods generation.

6.4.3 Tested scenarios

Two scenarios have been implemented with different input parameters. The purpose is to estimate the range of the obtained values with a “maximum” and a “minimum” scenario.
The following parameters have been considered:

Table 8 : Parameters for min / max scenarios

Variable parameters	Scenario 1 (max)	Scenario 2 (min)
100y daily rainfall (mm)	115	90
Storm area on each catchment (km²)	50	30
Soil type (CN method)	C	D

Curve number computation: For each watershed, a composite curve number has been calculated considering the land use data provided by the RNRA and presented in chapter 1.5.4.

Soil types: The encountered soil types have been indexed C or D. Unless being an american SCS expert used to this work, it is impossible to clearly define which kind of soil the catchment is made of. In the United States, the whole territory has been divided into 13600 areas indexed A, B C or D, therefore this parameter is not supposed to be a variable while it is in Rwanda.

Rainfall distributions: two storm areas have been considered: 30 or 50 km², meaning larger watersheds receive a limited amount of rain. On the contrary, small watersheds will receive rainfalls on their whole surface. For example, a 40 km² watershed will receive rainfalls on 40km² for scenario 1 and on 30km² for scenario 2.

The other parameters stay put: loss and transform methods are SCS curve number, no base flow computed, Muskingum routing method, no canopy.

A test has been performed with HEC RAS to estimate the flood damping of the wide Sebeya floodplain made of tea plantations. The result is that this effect is negligible: peak discharge is only reduced by 4% between the upper flood plain and Mahoko village (6 km).

Another test has been performed at the confluence of Karambo River. It shows that, due to the backwater in the upstream part of the Sebeya River, the effect is more important: a peak discharge of 118 m^3/s is reduced to 100 m^3/s that means a reduction of 15%.

6.4.4 Results scenario 1 (max)

Resulting hydrographs are provided below.

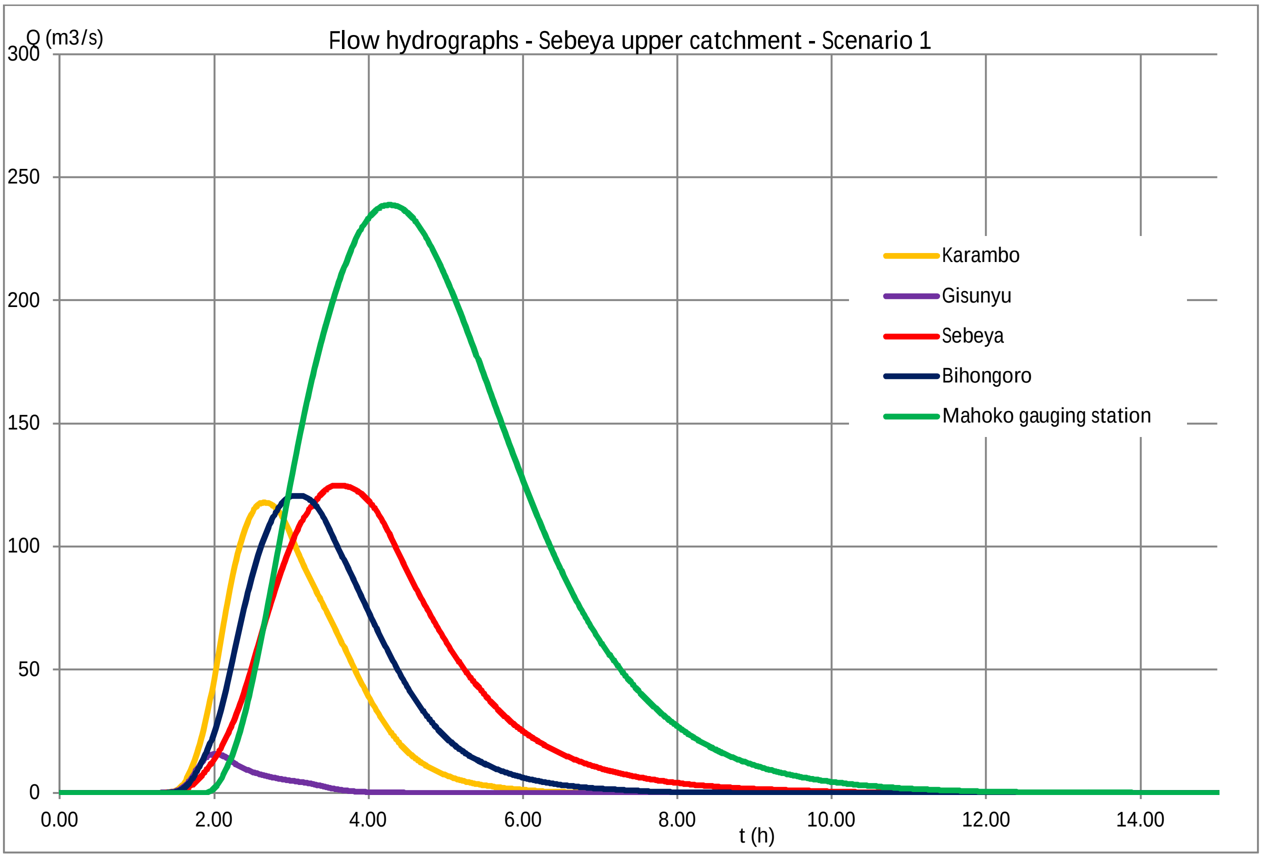


Figure 100 : Flow hydrograph - Sebeya River upper catchment - Scenario 1

Assuming rainfalls do not concern the whole four catchment areas at the same time, the combined hydrograph in Mahoko gauging station (see above) is not significant.
In fact, we can consider that the three most important catchments generate totally independent floods. We can see that the peak discharges are almost identical (approximately 120 m^3/s) so downstream the confluence of these three rivers, the return period of these discharge is 100/3 = 33 years.
So, to find the 100y return period discharge, we have estimated the 300y return period flood: the results are the following ones:

- Karambo: 150 m^3/s
- Bihongoro: 154 m^3/s
- Sebeya: 157 m^3/s

So Q100 at Nyundo gauging should be about **155 m^3/s.**

6.4.5 Results scenario 2 (min)

Resulting hydrographs are provided below.

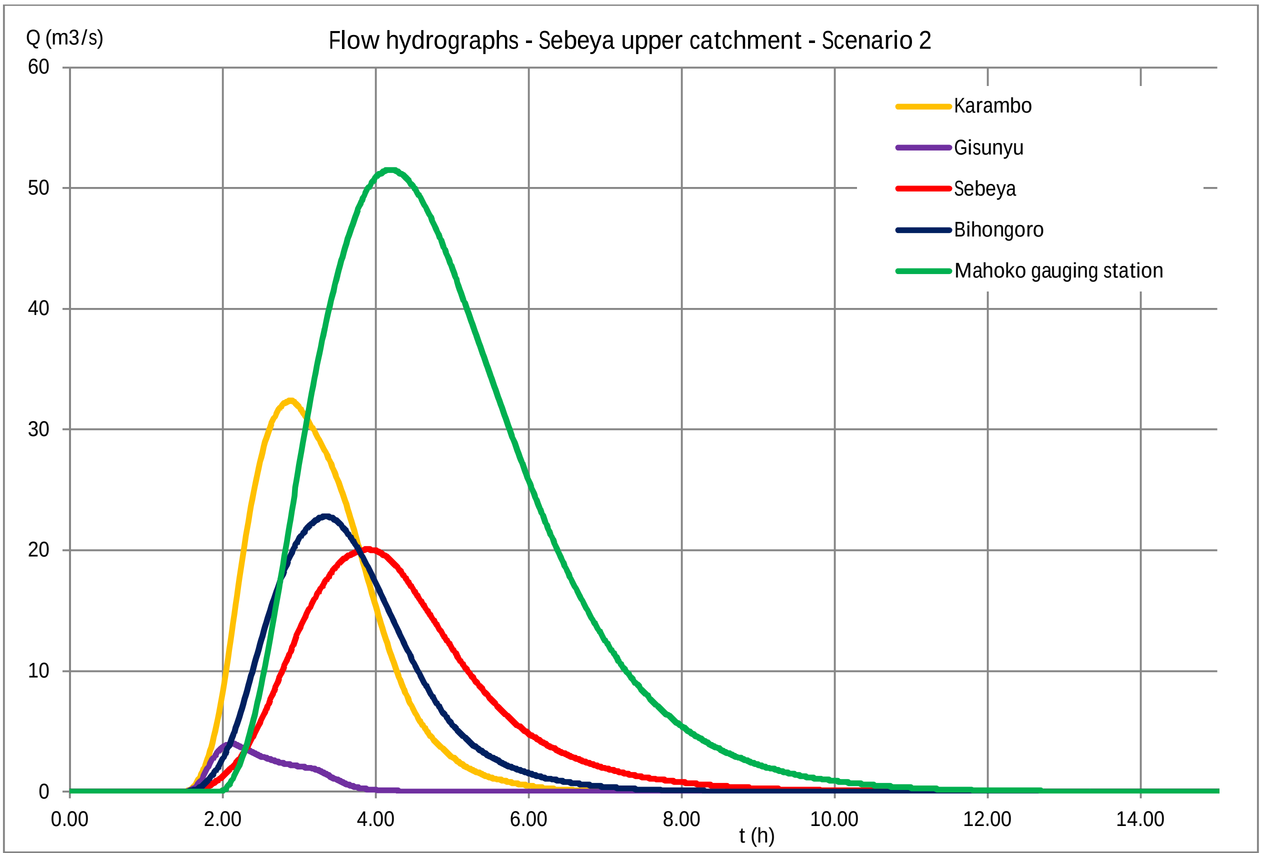


Figure 101 : Flow hydrograph - Sebeya River upper catchment - Scenario 2

As previously seen, the 33y flood downstream the three main subcatchments is approximately 25 m^3/s. Performing the same way of calculations than previously explained, the 100y return period flood at Nyundo is around **40 m^3/s.**

6.4.6 Conclusion

The range of possible results is too wide to estimate a value. This is due to many uncertainties:

- Ø Soil series (CN determination): these "soil series" have been determined by the SCS in the United States only. The way of sorting soils results from geological analysis and experiments that have not been done in Rwanda. Therefore, hypotheses have to be made on this parameter.
- Ø The spatial distribution of rains is heterogeneous and rainfalls probably only concern local areas which do not exceed 30 or 50 km^2.

Calculated 100y values thanks to CN method vary from 40 to 155 m^3/s. The probabilistic value of 72 m^3/s is contained into this interval, also the maximum interval found previously with probabilistic and statistic methods [60 m^3/s – 82 m^3/s].

Therefore, a hydrologic model cannot predict exactly what happens on a catchment. This also highlights the fact that a field survey is essential to estimate the real occurred events and criticize the data coming from the gauging station (which were wrong due to a false rating curve).

It is possible to improve in a scientific way the knowledge of runoff coefficient. But it needs some data to calibrate it:

- River discharge measurements (in fact height measurements and then a well-established relation between heights and discharges, with overflowing conditions).
- Rain-gauges on the catchment.
  - Ø As it is seen in the last chapters, related to implementation of early warning system, with convective phenomenon, the necessary density of rain-gauges is huge (18 rain gauges for 50 km² catchment).

Further problems are that:

- A same rainfall can produce different hydrographs (and peak discharges) due to the fact it depends on historic of precedent rainfall: if the soil is dry, infiltration will be more than with a wet soil.
  - Ø Thus it is necessary to have a large number of situations.
- Runoff coefficients vary with return period.
  - Ø In reality some phenomenon are not proportional to rainfall but reach a maximum limit: for example rainfall storage on leaves or on the surface of the land.
  - Ø Underground storage can also encounter a limit (then we say there is saturation of the groundwater). For example, in France this saturation is observed in the South, where 100 years daily rainfall is more than 200 mm; in the North it is less than 100 mm so saturation can be encountered only for very rare phenomenon (more than 100 years return period).
  - Ø It means that it is necessary to have a large number of ten-year floods to determine the ten-year average runoff coefficient.

For catchments of volcanic nature, another difficulty is connected to the heterogeneousness of lava flows. Each lava flow produces some cavities and tubes in which the water can flows.
So, we were able to study, on the island of Mayotte, in the Indian Ocean, two nearby catchments of the same volcanic nature and both equipped of measurement station.
The observations and the statistical analysis showed that frequent discharges were different.
Nevertheless, we had no data to determine 100y discharges. It is possible that this heterogeneity has no effect for rare flood because underground is nearer saturated situation.
Study of this needs a lot of good measurements on a rather long period.

7. Hydraulic study

7.1 Hydraulic modelling

Hydraulic models have been built on almost each river for different purposes:

- To calculate a range of discharge for a flooding on local parts of the river where high water marks have been recorded;
- On longer river sections, to check the capacity of the channel. For example, on Rwebeya River, the urban part of the river has been modelled to check if any overflow occur for 100y return period;
- On the endorheic rivers, to estimate the distribution of the flood volumes between different storage areas.
- To estimate flood damping (e.g. Sebeya & Pfunda rivers).
- To map the flood prone area

7.1.1 Topographic data available

The topographic data available for building hydraulic models are the following:

- Dem 10, provided by the RNRA. It is a raster image with a spatial resolution of 10 meters (one elevation point every 10 meters). It has been implemented in 2008 from aerial photographs tanks to stereoscopy technology.

  This data source is poor for three reasons:

  - Cell size of 10m is not accurate enough. Most of the river beds in the study area are tinier than the cell size so the information on bed depth is not available.
  - The raster image is "integer type" which means contained elevations are integer numbers (no decimals).
  - It is a digital surface model: no cleaning has been done and displayed elevations contain ground and other objects (trees, buildings, crops...) which not relevant. Only bare ground elevations are usefull for modelling.

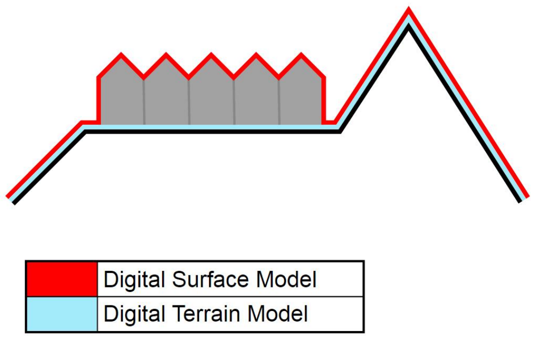


Figure 102: Difference between surface and terrain models (source: Wikipedia)

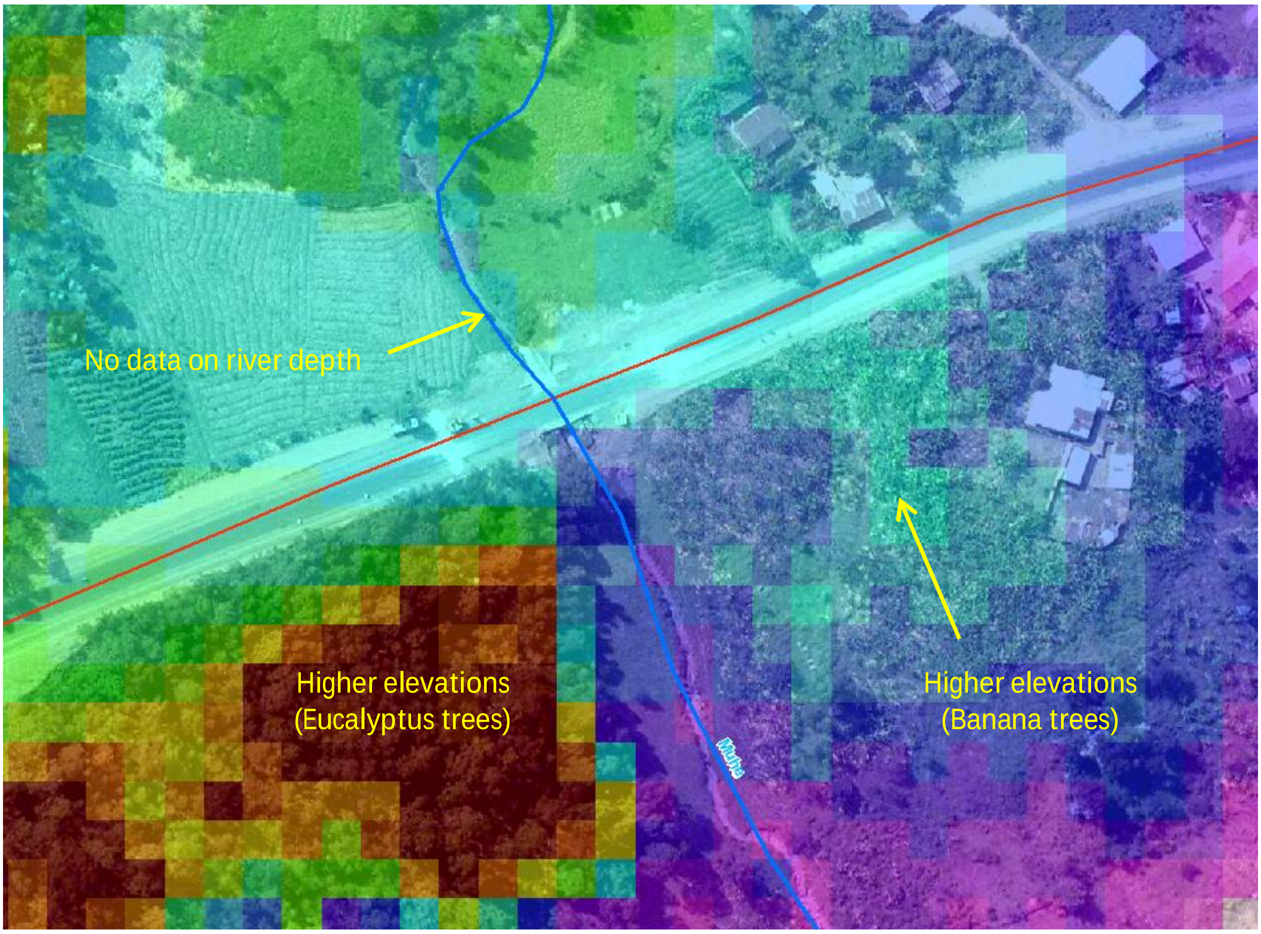


Figure 103: Example of dem10 data, Muhe bridge

- SRTM 30, is a worldwide terrain database (space radar technology). This data has not been used because worse than dem10.
- Man-made measures: during the field visits, cross sections and hydraulic structures have been measured, in particular places. Absolute elevations are barely calculated from dem10.

7.1.2 Software used

Hydraulic model of the different river beds will be built with HEC-RAS software. This software has been developed by US Army Corps of Engineers and is free distributed.
http://www.hec.usace.army.mil/software/hec-ras/

It is an integrated system of software which allows us to perform one-dimensional steady and unsteady flow river hydraulics calculations.

The steady flow component is capable of modelling subcritical, supercritical, and mixed flow regime water surface profiles.
Due to high slopes of the natural river beds (> 1%), the regime to be considered will be critical one.

7.2 Results

7.2.1 Rivers Rwebeya, Muhe and Susa

The 100 years flood calculations have been performed with estimated discharge provided in the hydrological study. Table underneath sums up these values:

Table 9 : Discharge values for 100 years return period flood

Place	Hydrologic Law type	Catchment area (km²)	Q_{100} (m^3/s)
Rwebeya (cycling center)	Upstream	5.5	69
Rwebeya (Road NR2 Bridge)	Downstream	31	55
Muhe (Kinigi Bridge)	Upstream	15	89

7.2.1.1 River Rwebeya

A hydraulic model has been built in the urban area of Musanze to enlighten the overflowing sectors for Q_{100}.

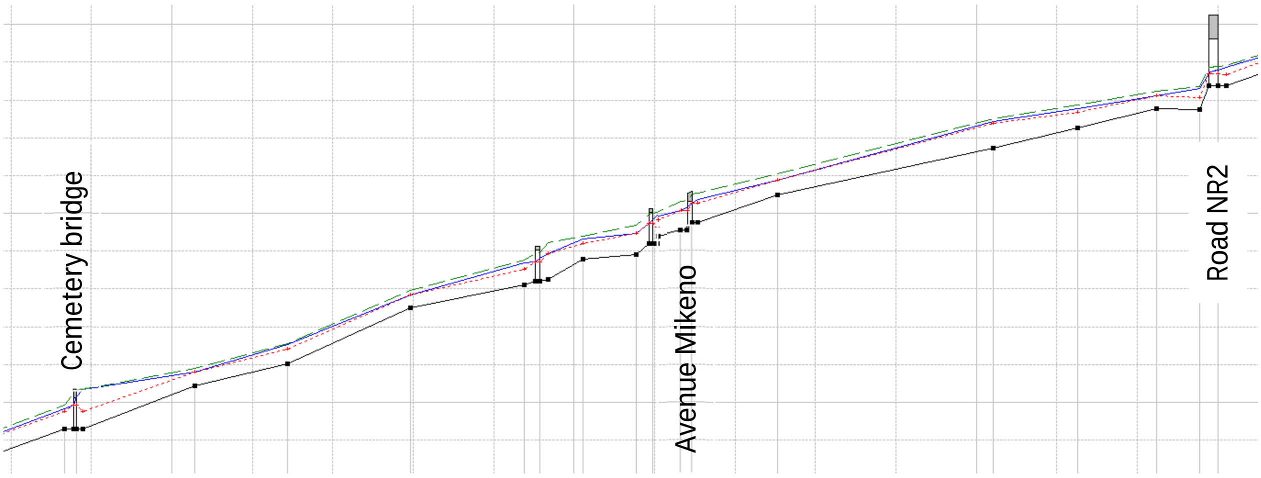


Figure 104: Length profile in Musanze urban area (Q100 Water and head levels)

For Q100, overflows are located:

- On a part of the cycling centre
- Avenue Mikeno's Bridge: the roadway is overtopped (overflows then continue on a parallel track, right bank);
- Cemetery Bridge (overtopped);
- Two other places downstream.

7.2.1.2 River Muhe and Susa

On these rivers, channels are sometimes above floodplains and most of the water flows out of them. Building a one dimensional model is not relevant in that case. A two dimensional model would have been more adapted, but time-consuming and above all useless according to the poor data available.

Models have been built only on key sectors (Main hydraulic structures, witnessed high water marks) to check capacities and calculate discharges for hydrological study.

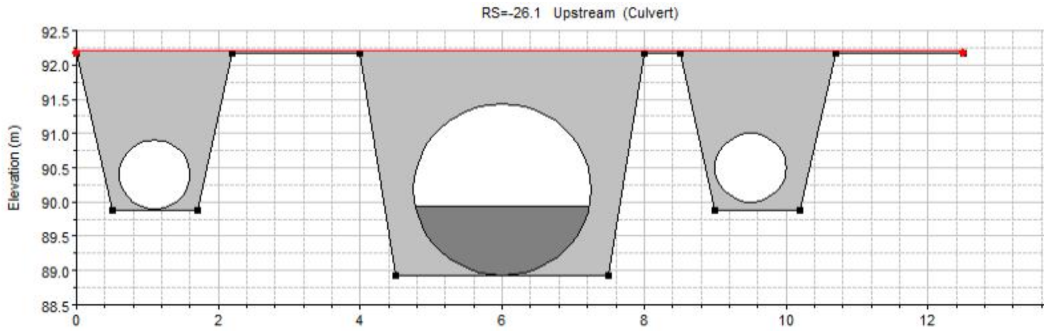


Figure 105: Example of hydraulic structure modelling: Bridge on river Muhe (road NR2)

7.2.1.3 River Mutobo

Mean Q_{100} discharge on this river is 35 m^3/s.
A hydraulic model has been built between the drinking water plant and the intake of Mutubo power plant. A steady flow analysis has been performed according to the fact there is no storage area (unlike Murufurwe River).

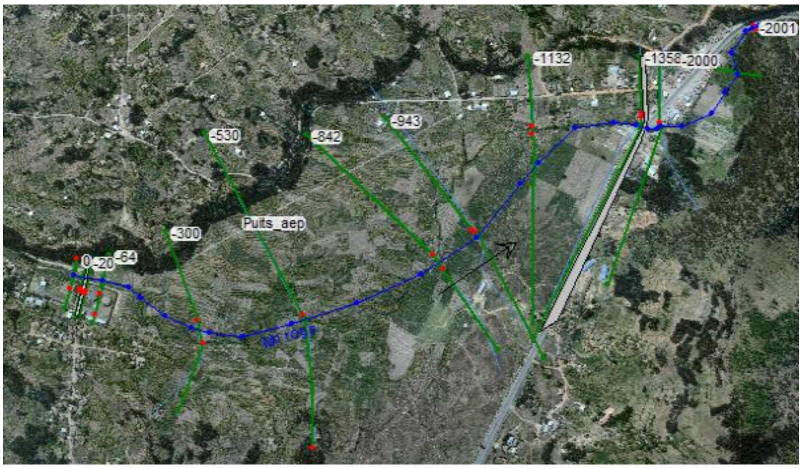


Figure 106: Schematic representation of Mutobo's hydraulic model

The analysis highlight that:

- Large overflows occur in the crop fields, downstream of the water drinking plant;
- The culvert under road NR2 is not overtopped, but upstream overflows submerge the inhabited areas on left bank;
- The houses downstream of the road are flooded (they currently partially already are, for 2016 event);
- Nearby the weir of the intake, water spills on the road left bank.

7.2.2 Endorheic rivers: Murufurwe, Rungu, Kinoni, Nyabitondore and Bikwi

7.2.2.1 River Murufurwe

Hypothesis

River Murufurwe is particular because a non-negligible part of the flood water (for intense events) is stored upstream of the bank of road NR2. It was necessary to build a hydraulic model representing both the river and the available storage areas. According to the fact we need to estimate the flood damping, it is mandatory to perform an unsteady flow analysis (Q = f(t)).
The model has been built according to the schematic below.

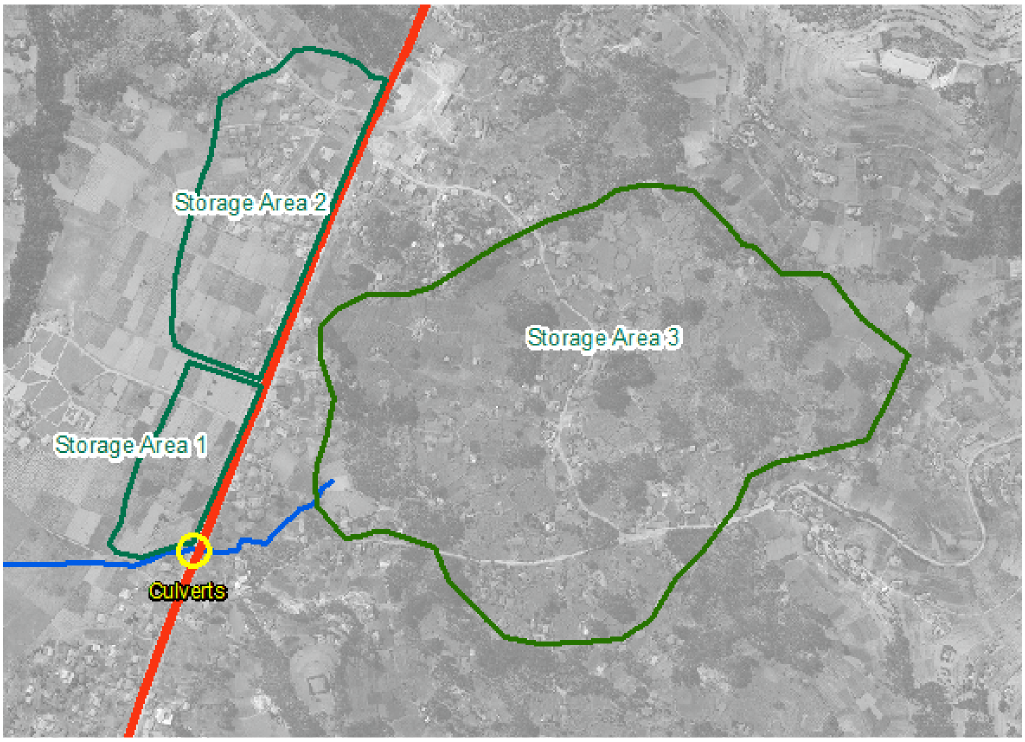
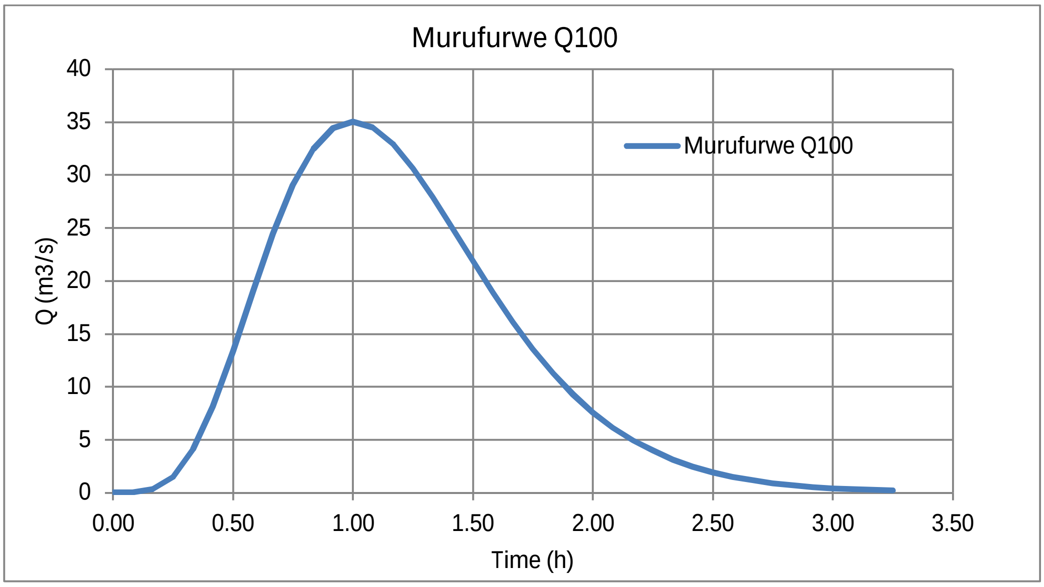


Figure 107: Schematic of Murufurwe hydraulic model

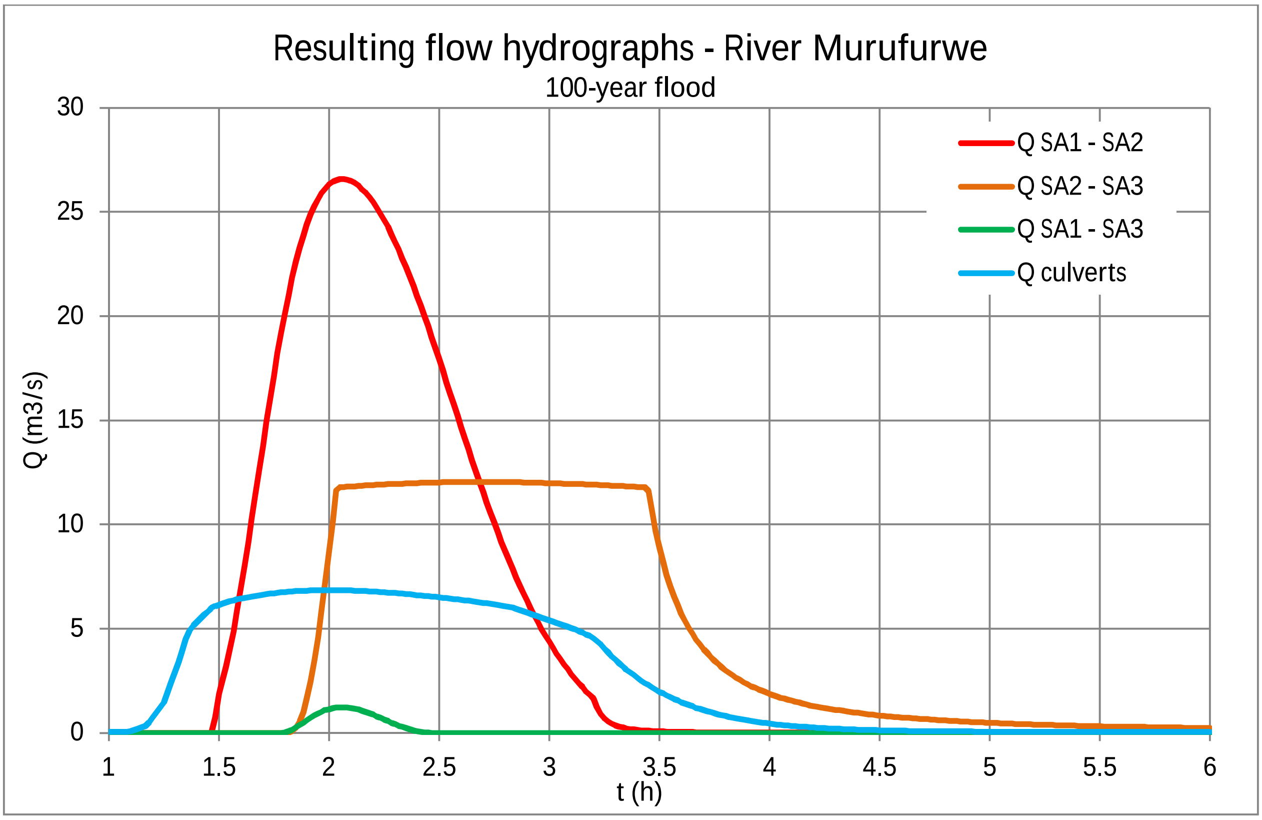
Link between storage areas (SA) are all weir type.

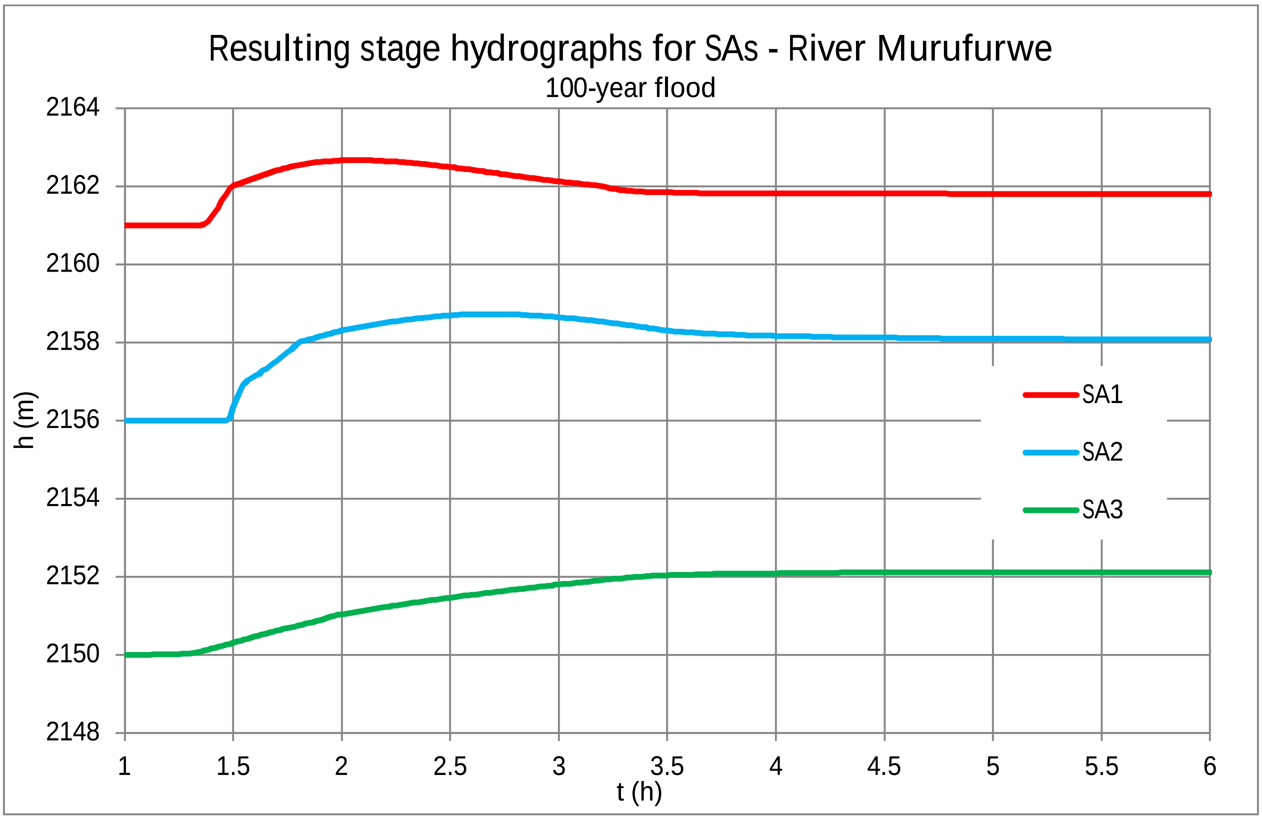
For the 100 year flood, the peak discharge is 35 m3/s and the “time to peak” about 1 hour. This results in the synthetic hydrograph below.



Results

The resulting hydrographs (flow and stage) are presented below.





Main conclusions:

- Maximum capacity of the culverts is $7m^3/s$;
- Roadway is overtopped in two places: next to the weir connexion between SA1 and SA2 (Qmax = $1.2m^3/s$) and at the low pass next to the school (Qmax = $12m^3/s$).

- Maximum reached water levels are 2162.66, 2158.72 and 2152.11 for respectively SA1, SA1 and SA3. Keep in mind the misleading appearance of accuracy in elevation figures (remember the digital elevation model is integer-type).
- North of the school, overflows may reach the pass and flow down the road towards Mutobo catchment.

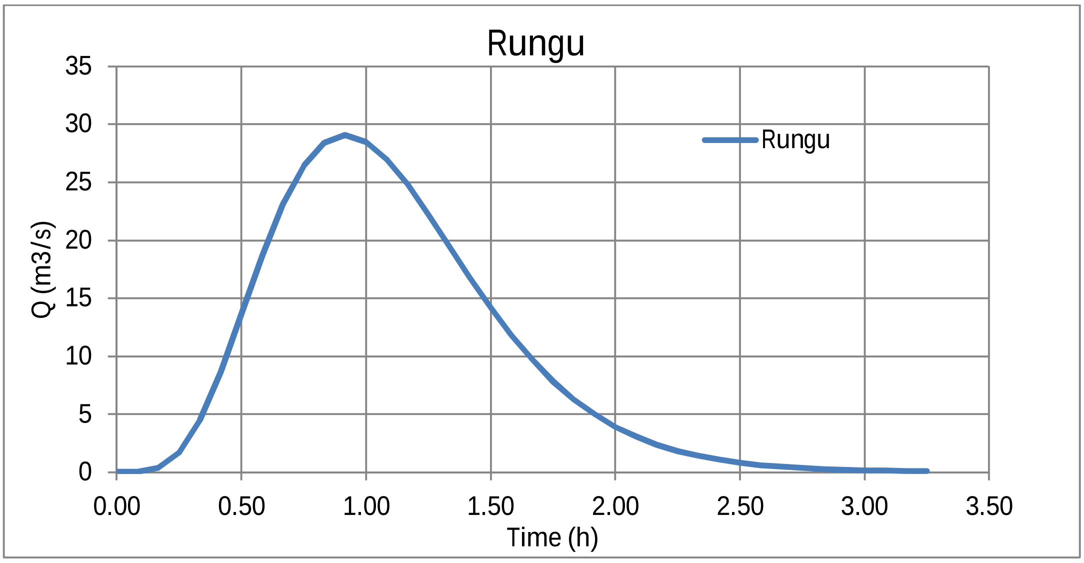
7.2.2.2 River Rungu

On this river, channel is dug into a terrain similar to an alluvial fan. Overflows occur sometimes and water gets lost into fields until infiltration absorbs them.
Building a one dimensional model is not relevant in that case. A two dimensional model would have been more adapted, but time-consuming and above all useless according to the poor data available.

Mapping methodology on this river is the following:

- Expertise mapping on the upstream part of the river:
  - High risk buffer zone has been mapped around the river where evidences of floods have been recorded;
  - Moderate risk zone around the previous one to highlight the fact residual water may come from Rungu's overflows.
- In the endorheic area where the river ends, the volume of the synthetic hydrograph computed is converted into water depth thanks to elevation-volume curve. No infiltration has been considered.
-

For the 100 year flood, the peak discharge is 29 m3/s and the "time to peak" about 1 hour. This results in the synthetic hydrograph below. Total volume is 112000 m^3.



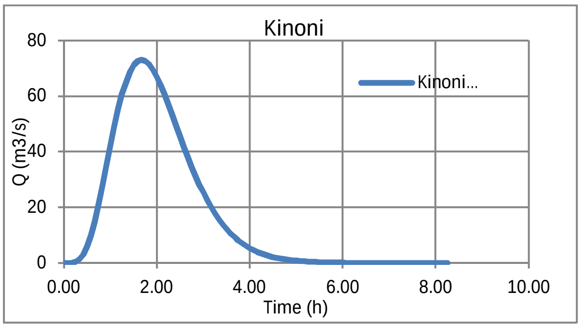
7.2.2.3 Rivers Kinoni and Nyabitondore

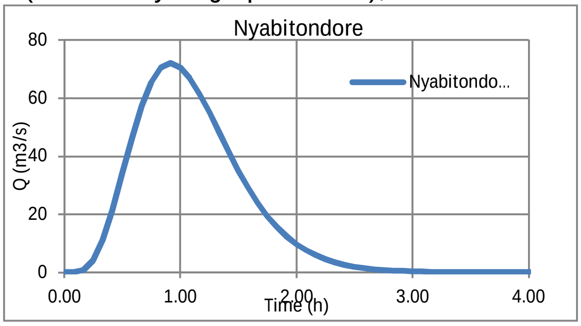
These streams are treated together because they both end into the Mugogo endorheic area where caves empty more or less this area.

hypothesis

The following hypotheses have been considered to study the area:

- Incoming 100y discharges from Kinoni and Nyabitondore: 73 and 72 m3/s with respectively a concentration time of 100 and 55 minutes (see flow hydrographs below);





- Despite the presence of caves, no infiltration has been considered (safety-side hypothesis);
- Both floods occur simultaneously (safety-side hypothesis).

To study the behaviour of these floods in the area, a small hydraulic model has been implemented. It is made of storage areas linked together exiting into the Mugogo endorheic area (name STO5 on the map below).

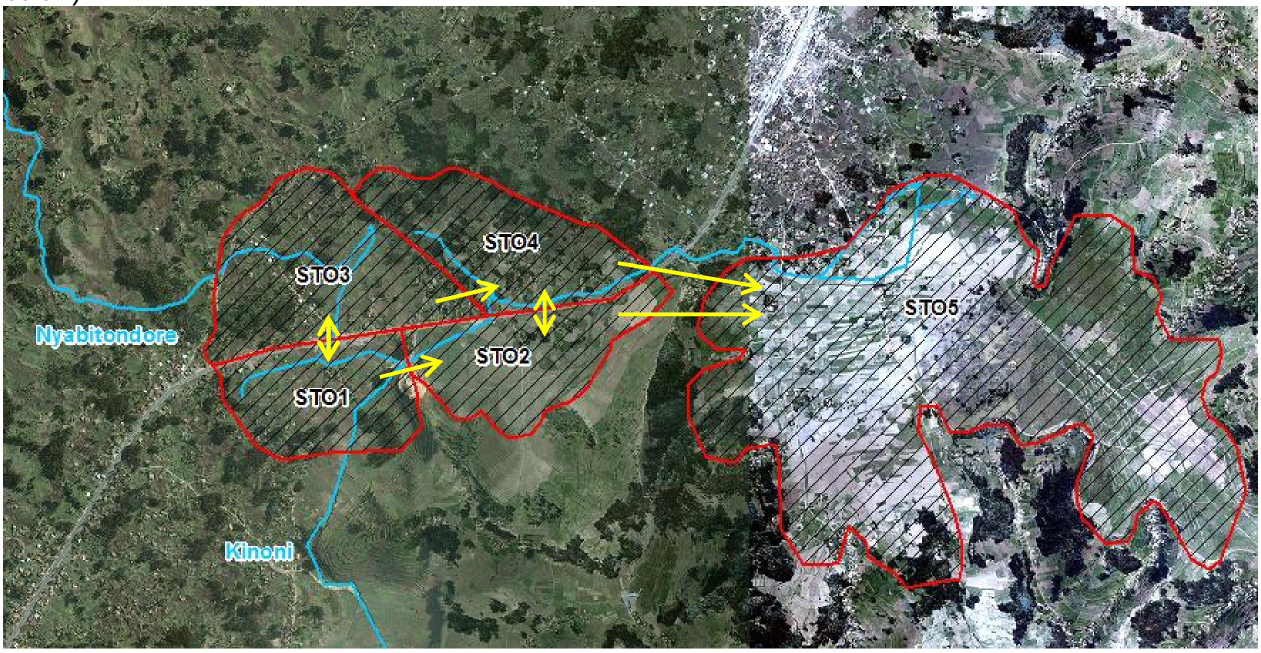


Figure 108 Schematic representation of Mugogo hydraulic model (links are the yellow arrows)

Results

- Kinoni and Nyabitondore rivers, when exiting the gully-part of their beds, widely spread into the floodplains made of tea plantation or miscellanous crops;
- A lake is appearing into Mugogo endorheic area, for the 100y return period flood, the level can rise up to 2160m (maximum depth of 4m);
- The road NR2 is locally overtopped.

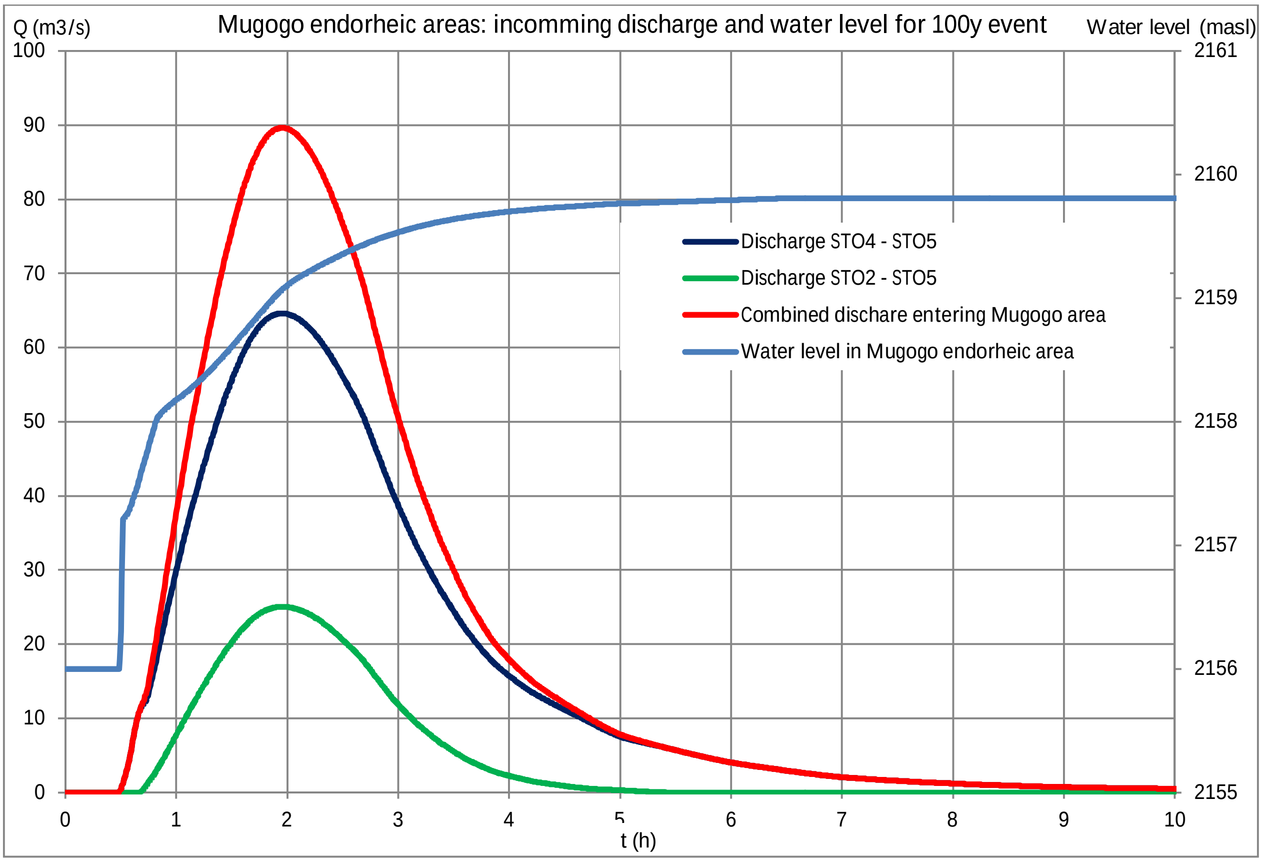


Figure 109: resulting stage and flow hydrographs for Mugogo endorheic area

7.2.2.4 Bikwi river

Bikwi river currently ends into a lowland upstream of road NR2. This lowland is technically not the natural exit of Bikwi river because a natural weir prevent the water from flowing further downstream towards Mugogo area. Until now, and according to the testimonies of local people, the river floods have always been contained into the lowland, and the natural weir has never spilled.

The most important flood occurred in May 2016 and the water filled the lowland 1 meter below the natural weir. Assuming the lowland was empty before the flood, it would mean a 30 m^3/s discharge entered the area (this value is uncertain because of parameters impossible to estimate such as the shape of the hydrograph, so we considered a classic exponential one).

For the previous caclulations, a flood damping model has been made around the two lowlands.

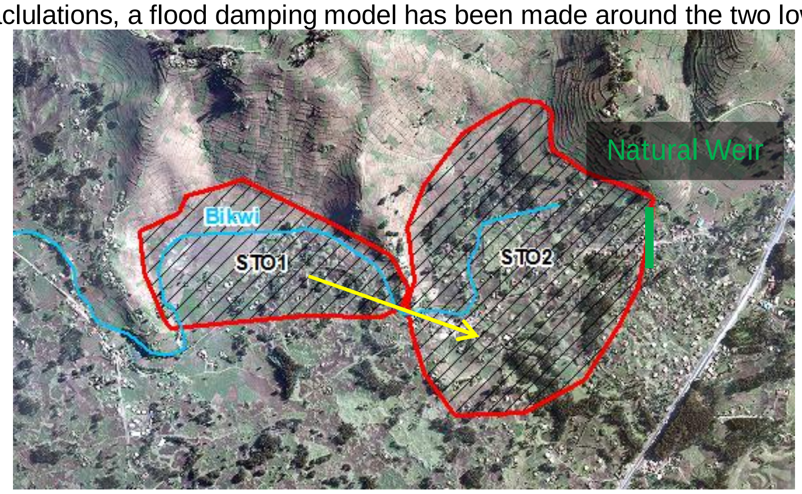


Figure 110 Schematic representation of Bikwi damping model (links are the yellow arrows)

Hypothesis

- If we consider the two formulas established is paragraph 0, 100y discharge in Bikwi would be 10 < Q < 120 m^3/s.
- Assuming Bikwi 2016 event frequency is similar to Kinoni (25 < T < 100), 100y flood is at least $30 m^3/s$ upstream of the lowlands.
- Uncertainty is too important on the discharge here. For mapping, we will consider that lowlands are entirely filled and that the natural weir can overflow (which will probably occur one day as the area is becoming more and more impervious).

Results

- Water is released from the natural weir once the 360 000 m^3 available for storage are filled.
- This is equivalent to a 50 m3/s flood (for a typical exponential hydrograph with tc = 2.5h, shape coef. = 5).

7.2.3 Sebeya and Pfunda Catchments

A hydraulic model has been implemented on both Pfunda and Sebeya rivers. It has been used for several purposes:

- Discharges determination from testimonies;
- Calculation of the new "Nyundo" rating curve;
- Flood mapping once 100y discharges calculated.

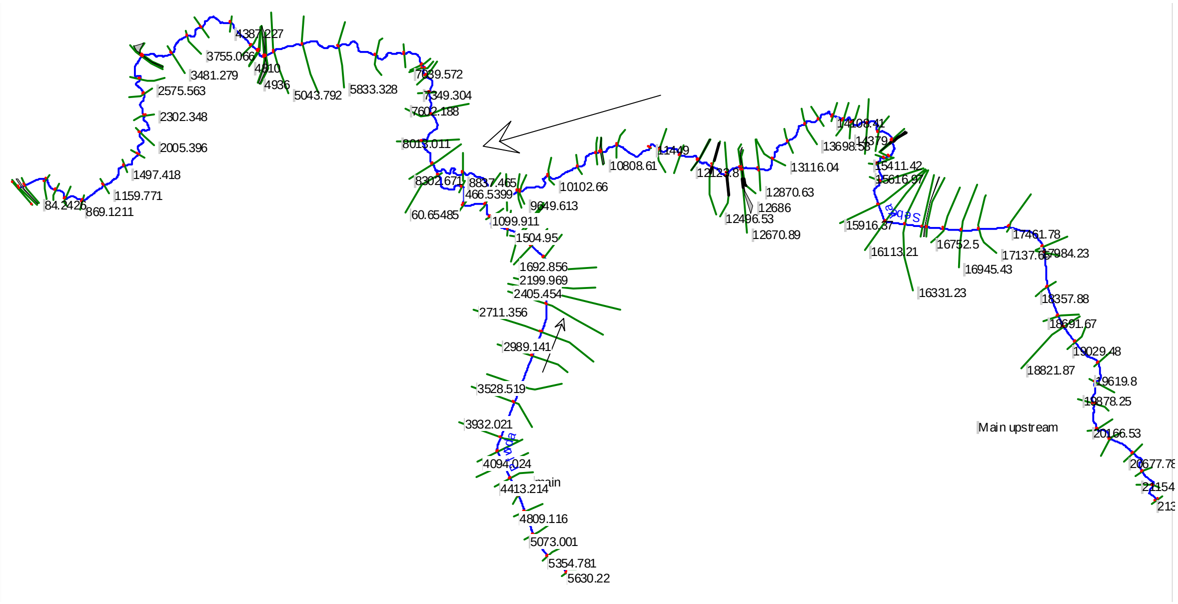


Figure 111 Schematic of Pfunda and Sebeya HEC-RAS hydraulic model

Hypothesis

The considered Q100 discharges for the hydraulic study are provided in the next table. These data come from the hydrologic study (cf. § 6.3).

Table 10 Mean Q100 discharges for Sebeya and Pfunda Rivers

River	Location	Catchment area (km²)	Mean Q_{100} (m^3/s)
Sebeya	Nyundo gauging station	210	74
Sebeya	Gihira	360	103
Pfunda	Upstream of confluence	59	48

Calculations have been performed with a steady flow analysis because an unsteady flow analysis cannot stand 10% slopes as existing in the Sebeya River. Nevertheless, the hydraulic model of Sebeya river has been cut into "low slopes" pieces to estimate the damping capacities of these parts: for example, Q100 discharge is only reduced by 4% upstream of Mahoko (in the flat tea plantations), which is a very low value.

Results

Resulting maps of the flood prone area are provided in Annex2.

8. Maps of flood prone areas

8.1 Definition of the risk

The flood risk is defined by two main parameters: water depth and velocity of the flow.
According to the intensity of these two parameters, a human being can resist more or less when caught into a flood.
The underneath diagram shows the limits of moving into water for different human beings:

- Athletic adult (red line);
- Non-athletic adult (blue line);
- Standing kid (green line).

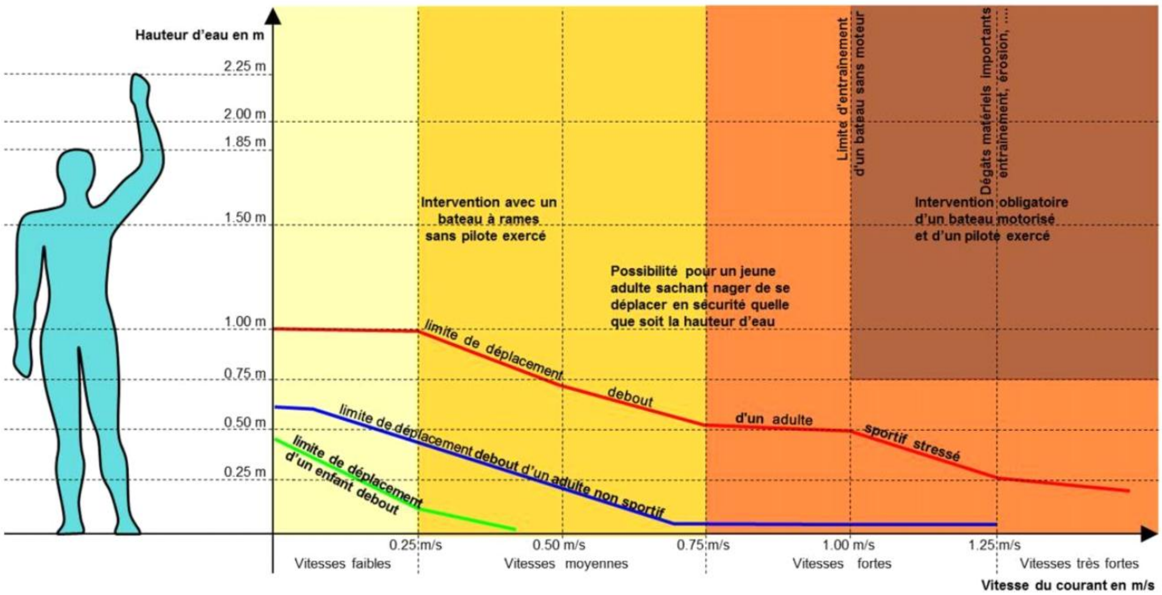


Figure 112: Human resistance to the flow

This diagram leads to a table more "readable" to introduce the three classes of risks: low, moderate and high. **These classes have been used in the current study.**

Table 11: Flood risk classification

Velocities (m/s) / Depth (m)	0 - 0.2	0.2 - 0.5	> 0.5
0 - 0.5	Low		
0.5 - 1		Moderate	
>1			High

8.2 Risk mapping

Mapping the risk requires to know the characteristics of the flow (see previous paragraph). This can be done using two methods:

- Ø Modelling,
- Ø Expertise, when no modelling is done.

Modelling can easily distinguish the different parameters of a flow and achieve a classification with 3 classes.
Expertise cannot be so accurate and is limited to “High” and “Medium” classes.
The maps are presented under a scale of 1/25000 for a best fit in report format but they can be used until a scale of 1/10000.

The flood risk maps are provided in annex 1.

8.3 GIS Shapefile

Layer’s name:
The provided layer containing floodplains is named “100y-Floodplain.shp”

Attributes:
The field “Flood_risk” contains numbers related to the three different classes of risk:
1 = Low
2 = Moderate
3 = High

Projection characteristics:

Projected Coordinate System:	*TM_Rwanda*
Projection:	*Transverse_Mercator*
Geographic Coordinate System:	*GCS_ITRF_2005*
Datum:	*ITRF_2005*

9. Mitigation works

9.1 General guidelines and proposed works

Implementation of mitigation works have to be studied as they are an important part of the project.
The work consists in giving technical solutions.
Feasibility study and detailed design must be led by local authorities (IWRMD, MINIMAR, District), later on, taking into account all local aspects.

Prior to enter the technical parts, this preamble's purpose is to highlight a particularity of the volcanoes catchments in order to understand the way the mitigation works are thought.
Indeed, the hydrological study (see chapter 4.) and sites visits have shown that:

- Mainly rainfalls on mountainous areas generate floods;
- Once entering larger valleys, rivers overflow and lose a very important part of their water. From that point, peak discharges decrease (some rivers never even end their way into another stream).

The way it currently works means mitigation works **have to be implemented very carefully and should try, as far as possible, not to concentrate the flow of streams to avoid the increase of floods downstream**. For instance, systematic containment of rivers is to be prohibited because if done so, will require further works downstream where the floods will be more frequent and important.

The following proposed works mainly consists in lateral protections against erosion, hydraulic structure resizing, river training, river diversion and very local containment. Some of the measures are catchment-scaled and require to be implemented widely to be efficient.

Table 12: Proposed works and priority (urgent = 1)

ID	River	Type	Comment	Proposed priority
1	Rwebeya	Bank protections	Lateral gabion protections to prevent banks collapsing	2
2	Rwebeya	Bridge fixing	Gabion weir to be built downstream on main road's bridge	1
3	Rwebeya	Deposition area	River bed enlargement for sediment deposition	2
4	Susa	River training	Enlarging the capacity of Susa river upstream of the main road and reconstruction of existing structures.	2
5	Susa & Muhe	Bridge reconstruction	Reconstruction of bridge under Gisenyi road (larger structure)	1/2
6	Mutobo	Levee	Levee to be constructed right bank along Wasac plant	3
7	Murufurwe	Embankment	Reconstruct houses to road's level (rising ground)	3

ID	River	Type	Comment	Proposed priority
8	Rungu	Levee	Levee to be built right bank to protect the university	3
9	Sebeya	Diversion channel	Mahoko diversion channel to be built	2
10	Sebeya	River training	River training near "Petit séminaire", Nyundo	2
11	Karambo / Gisunyu	Bridge fixing	Strengthening Gisunyu's gully damaged bridge	1
12	Whole area		Locate news appearance of new gullies and act appropriately	1
13	Whole area		Encourage new agricultural practices aiming at soil conservation	2
14	Whole area		Early warning systems	3
15	Whole area	Water storage		NA
16	Whole area	Reducing water velocity		NA

These works are located on the maps below.

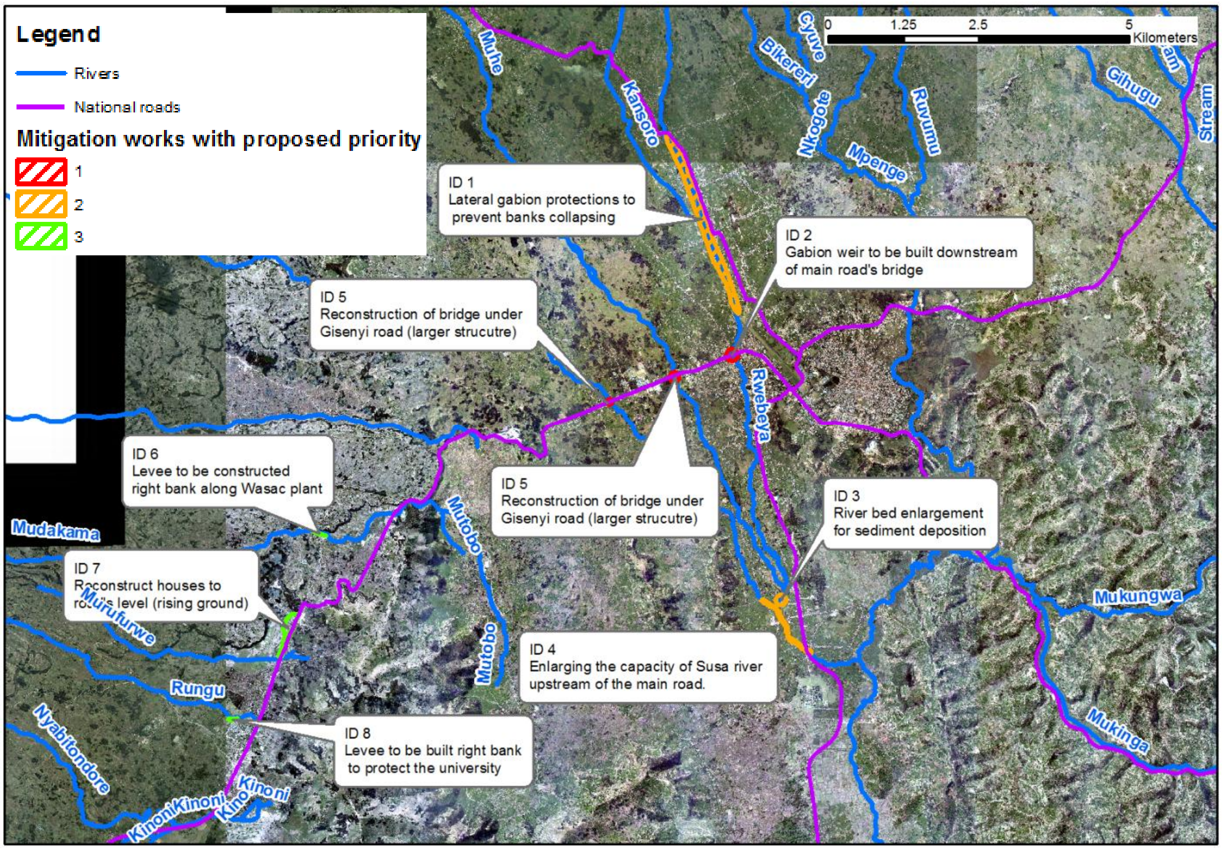


Figure 113 Proposed mitigation works in Musanze area

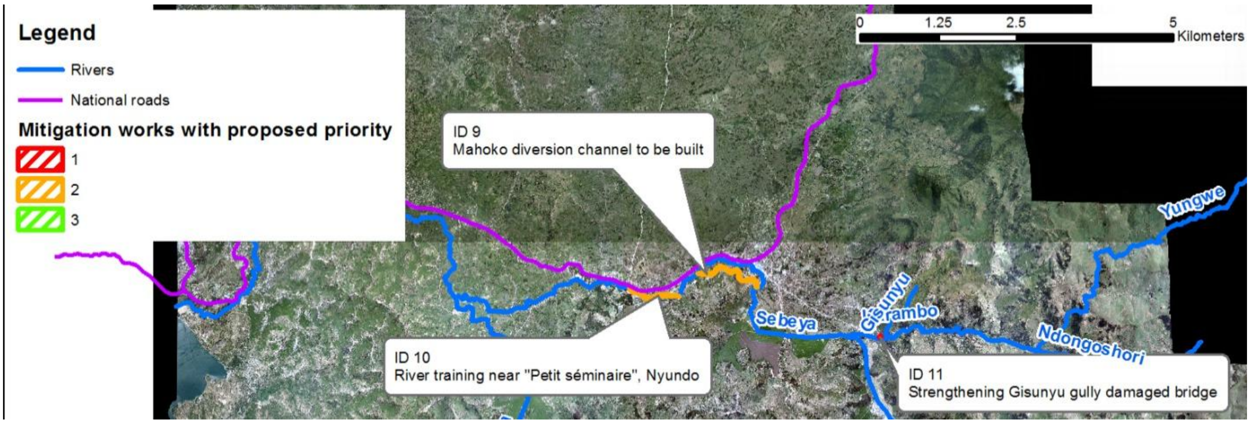


Figure 114 Proposed mitigation works in Sebeya area

Each proposed solution will require further studies with more accurate topography. Provided design can't be implemented without being revised.

9.2 ID 1 – Rwebeya River banks protections.

9.2.1 Location

Upstream of Musanze, some protections are locally needed to avoid further lateral erosions (see 2.1.2.1). These protections are to be placed only in the vicinities of threatened areas. No specific design will be provided hereunder: just a typical cross section to be adapted according to the cross section.

Figure 115 Threatened embankments requiring lateral protections

9.2.2 Hydraulic specifications

The specifications of Rwebeya River, in the concerned area, are the following:

- Slope from 2 to 2.5%;
- Critical flow;
- Rectangular cross section;
- Width ranges from 5 to 10 meters.
- 100y return period discharge: 70 m^3/s

Such protections have to be dimensioned for an important flood because they might be destroyed in case of submergence. Top of protections should be elevated up to 50 cm above energy head.

Table 13: Flow specification for Rwebeya typical rectangular cross section (Q100 = 70 m3/s)

	L = 5m	L = 10m
Critical depth (m)	2.76	1.7
Energy head (m)	4.14	2.53
Velocity (m/s)	4.9	3.9
Supposed scour – Isbach formula (m)	2.3	2.2

9.2.3 Specifications

1 m^3 gabions boxes will be used to make the lateral protections and Reno mattress for the bottom protections against scour.
Geotextile will be added at each contact area between gabion / Reno mattresses and the natural ground.

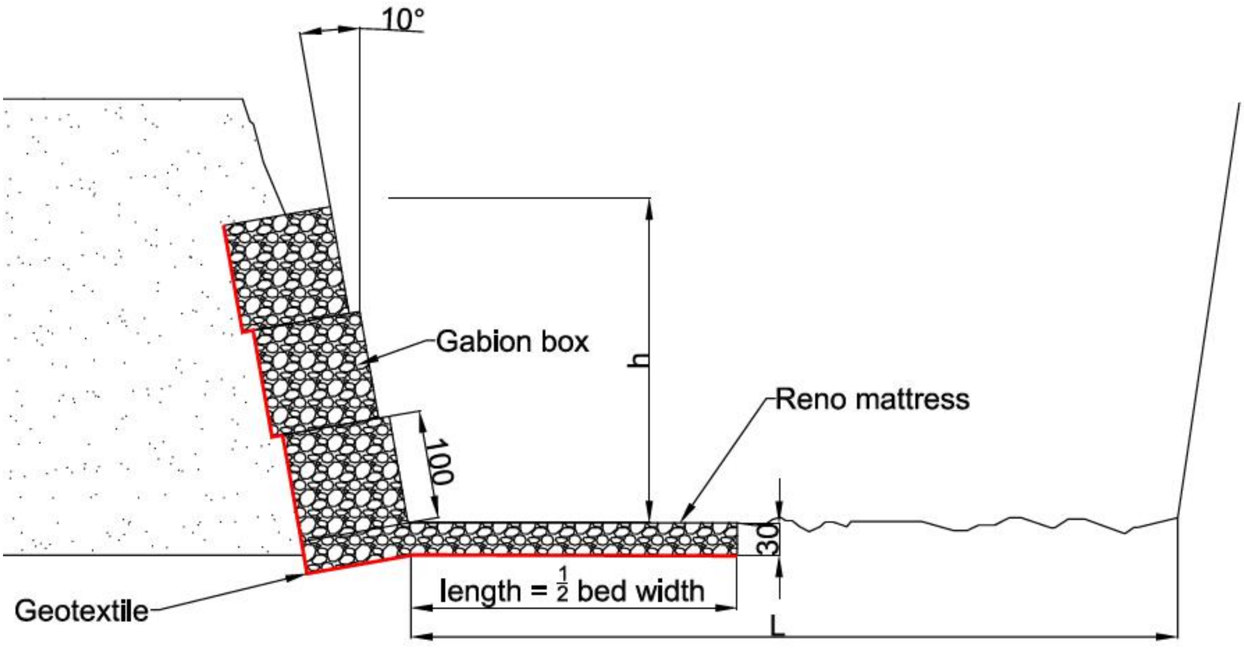


Figure 116 Standard pattern for Rwebeya lateral protections (units = centimeters)

Before starting works, it is necessary to be sure that the bed level is stable in case of alluvial river beds. Gabions and Reno mattresses have to be laid on properly excavated soil: superficial layers have to be removed, even those from bedrock (sometimes disintegrated).

9.3 ID 2 – Rwebeya main bridge fixing

9.3.1 Location

The Bridge of the national road NR2 is damaged downstream were erosion is currently digging under the slab. Repair works have to be done quickly.

Figure 117 Rwebeya bridge in Musanze-city

9.3.2 Hydraulic specifications

The hydraulic specifications of the river are the following:

- 100y discharge: 70 m3/s;
- Width of the Bridge: 12m;
- Height of the drop downstream of the Bridge: 2.5m;
- Slope of the river downstream of the Bridge: 2 %;
- Computed velocities downstream of the bridge: 3.4 m/s;

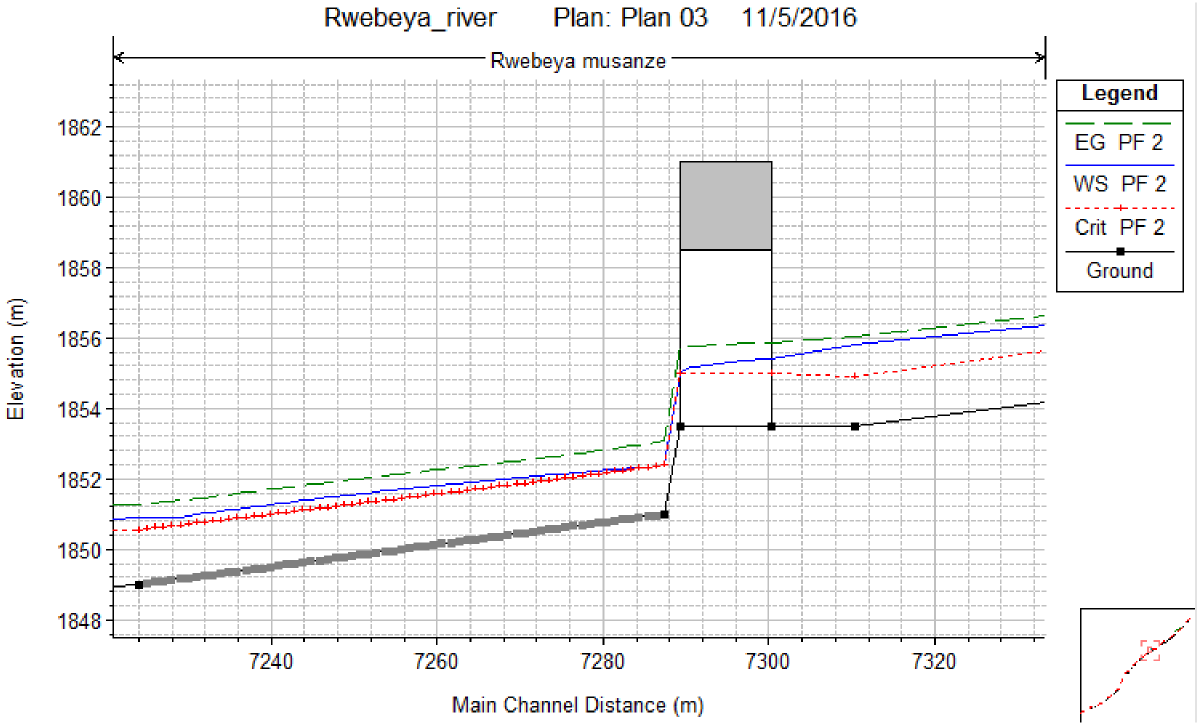


Figure 118 Longitudinal profile for Q100 = 70 m3/s

Purposes of repair works will consist of:

- Strengthening the Bridge by pouring concrete into scour holes under the slab;
- Build a stepped weir in order to shift the hydraulic jump further downstream.

9.3.3 Specifications

Prior to build the weir up, the scour holes under the bridge's slab have to be filled with concrete.
Then, 1 m^3 gabions boxes will be used to make the weir and the lateral protections. Reno mattress will be used downstream the weir to prevent scouring.
Geotextile will be added at each contact area between gabion / Reno mattresses and the natural ground.

A particular surveillance of the evolution of the bed level has to be performed due to probable on-going bed lowering.

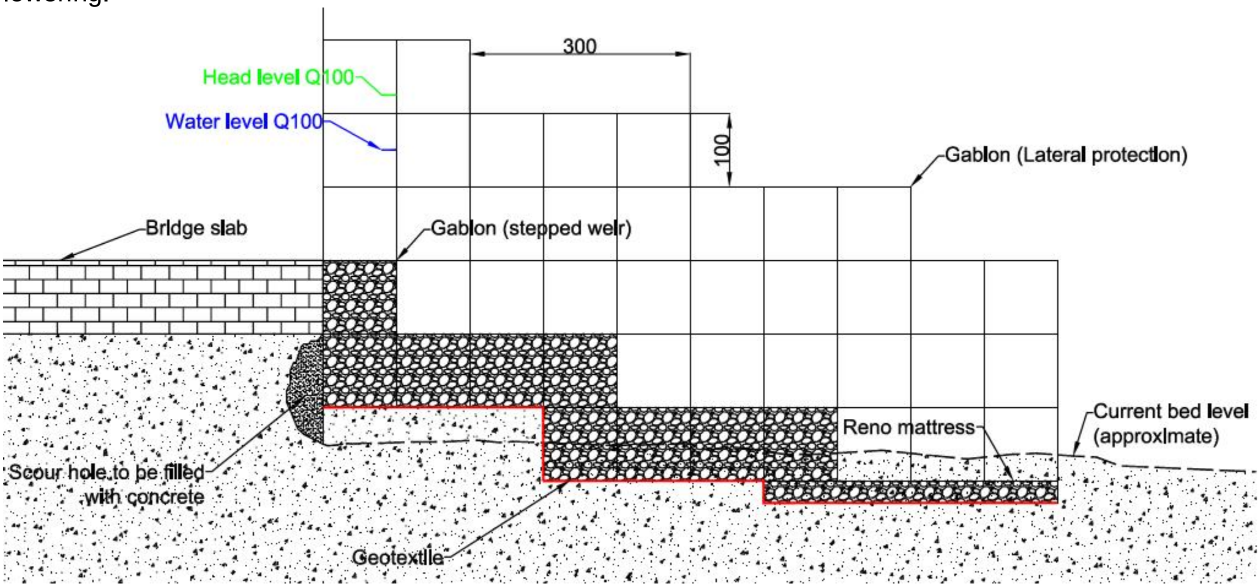


Figure 119: Stepped weir downstream of Rwebeya road NR2 Bridge - Longitudinal profile

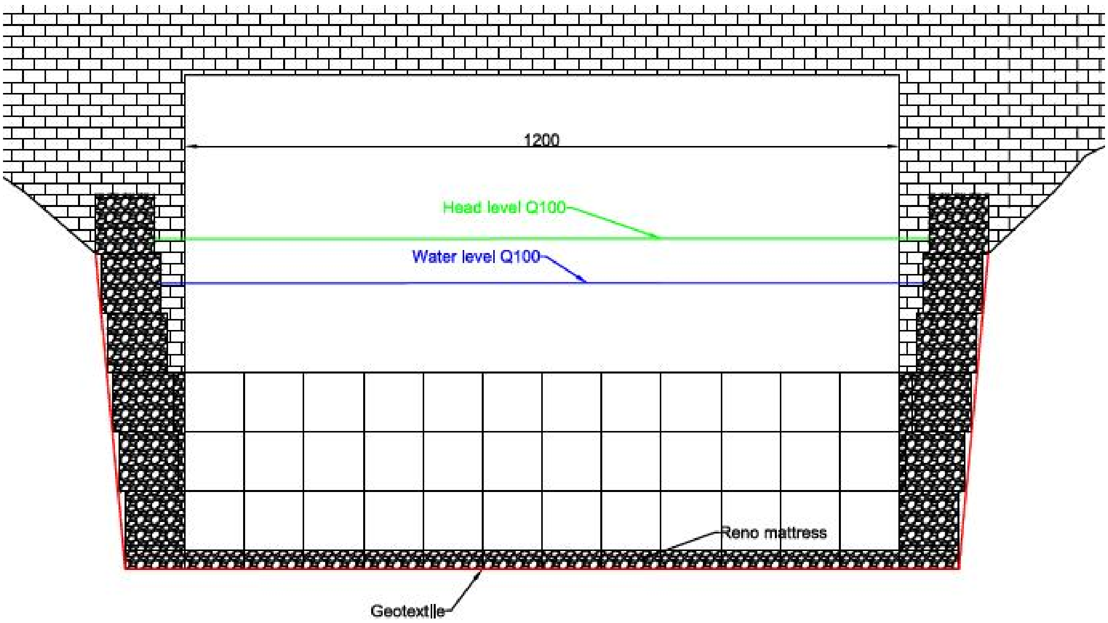


Figure 120: Stepped weir downstream of Rwebeya road NR2 Bridge – view from downstream

9.4 ID 3 – Debris basin

9.4.1 Location

Downstream of the confluence between Rwebeya and Muhe rivers, the bed slope decreases (from 3 to 1.3%). This already induces the deposition of sediments which cause lateral overflows.
The purpose is to uphold this way of functioning by creating a debris basin in which large quantities of sediments will get stuck.
This work will lead to reducing the overflows in the vicinities and downstream of the debris basin.
The following schemes will only show principles and typical cross section of such works: an additional study will have to be made to implement this kind of structure and gather other paramount data (accurate topography, estimation of sediment volumes to store, soil analysis etc.)

The area to be reworked is shown below.

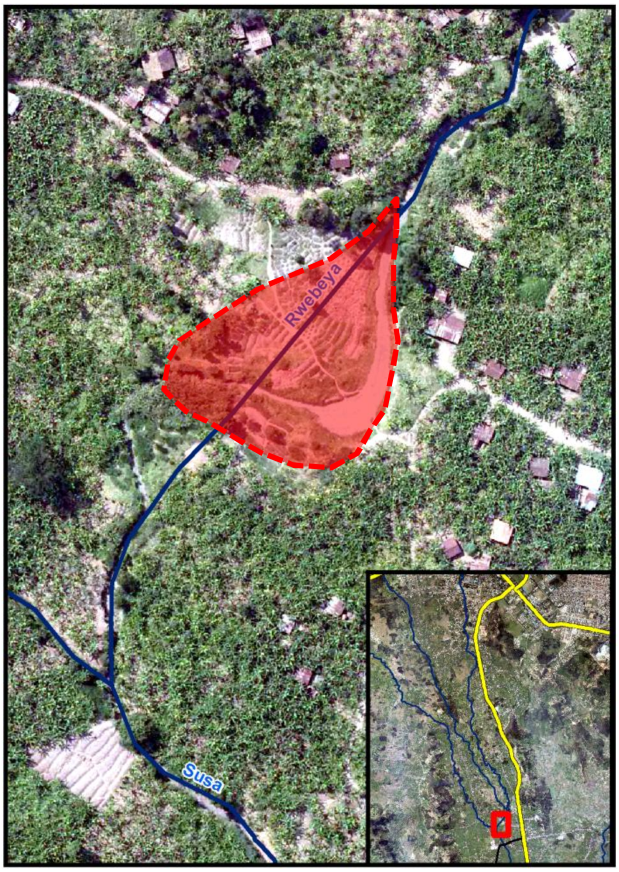


Figure 121 Location of the debris basin

Figure 122 Area to be reworked into a debris basin (downstream view)

9.4.2 Specifications

The debris basins mainly consist of:

- Enlarging the river channel to create a storage area;
- Building a straining structure downstream of the basin to generate head loss.

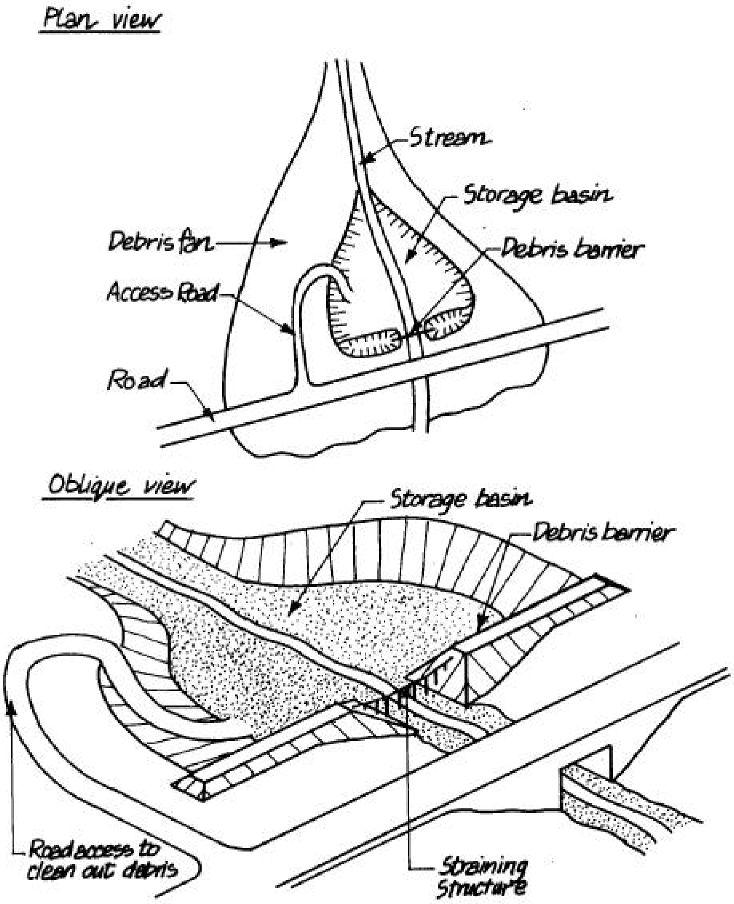


Figure 123 Typical components of a debris basin (source: D.F VanDine - Ministry of Forests and research Program – British Columbia)

9.4.2.1 Excavation works

The current bed slope is about 1.5%. Excavations can be made until reaching a lower slope (even 0%). There is no risk of regressive erosion due to the presence of bedrock right upstream of the project.

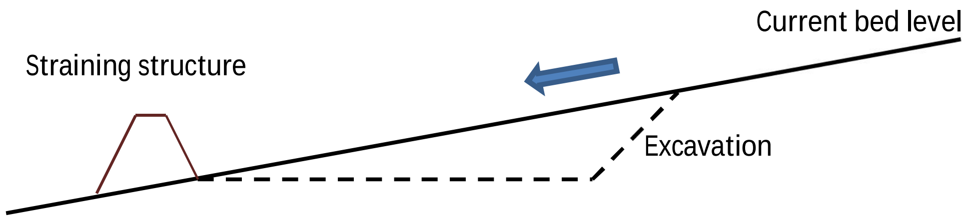


Figure 124 Debris basin schematic longitudinal profile

The proposed excavations could concern the following area and typical cross sections (see below)

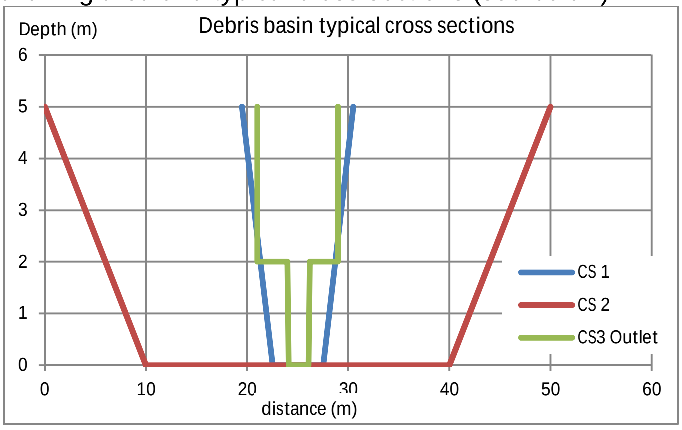


Figure 125 Excavations for debris basin

9.4.3 Straining structure

In order to facilitate sediment deposition into the basin, a straining structure has to be made at the basin outlet. This structure will generate a head loss and slow down the velocity into the basin.

The structure will be made as a transversal dyke (or reinforced concrete wall) with a small opening in stream axis. Because of high flow velocities, this opening has to be hardened with concrete or a combination of rockfill and concrete.

Typical shape of this structure is shown below:

- At the bottom, flow is contracted with a 2x2m opening, enabling sediment drop for low flows.
- For higher discharges, waters spills over the entire width of the structure (l=6.5m).

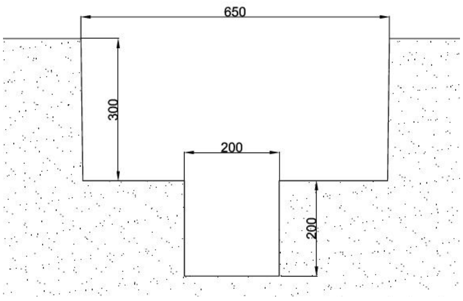


Figure 126 Straining structure

The structure has been designed for a 100y discharge of 79 m^3/s.

9.5 ID 4 – River training

9.5.1 Location

At the confluence of rivers Rwebeya and Susa, the floodplain is widely flooded due to the lack of capacity of the Susa river channel. Moreover, the situation is worsened by the deposition of sediments.
The following works will improve the capacity of river:

- Ø Enlarging the river channel and hydraulic structures;
- Ø Building a debris basin (previously proposed) to get rid of the sediments so that the river training can be efficient.

In all cases, the river training can't be implemented unless debris basin is made.

The total length of the river training is 1.3 km. Four hydraulic structures will have to be rebuilt because of their insufficient current capacities.

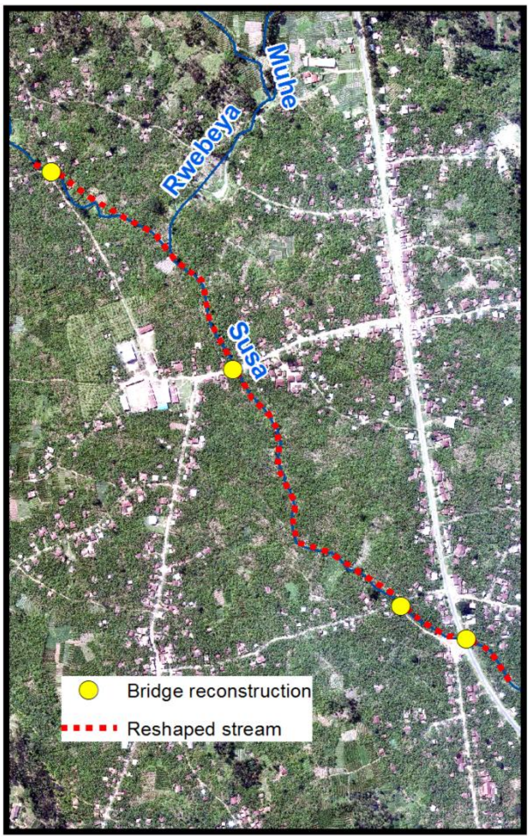


Figure 127 Proposed river training

9.5.2 Hydraulic specifications

Considering the high importance of the proposed works (large excavations, bridges replacement), a high grade of protection should be considered for design.
The project discharge should be chosen according to the following facts:

- Ø The 2016 flood overtopped the main road's bridge which means Q > 40 m^3/s;
- Ø The 100y return period flood calculated downstream of Sebeya and Rwebeya rivers (cf. equation 0) is 100 m^3/s.
- Ø Upstream of their confluence, 100y discharge for Rwebeya is 79 m^3/s and 77 m^3/s for Susa.

The 100y calculated discharge (100 m^3/s) is certainly overestimated because it has been calculated thanks to a formula that works for smaller basins considered at Gisenyi Road. As no significant inflows meanwhile reach the rivers, the 100y discharge may be less. Moreover, the probability of having simultaneous floods of Susa and Rwebeya rivers is very small.

The Project discharge we consider for the design is **80 m^3/s**.

9.5.3 Specifications

9.5.3.1 Excavations

Excavations have to be made differently depending on the encountered soil:

- Trapezoidal shape if no bedrock (alluvial soil);
- Rectangular shape if presence of bedrock.

The bed slope has to be maintained at its original value of 1.5%.

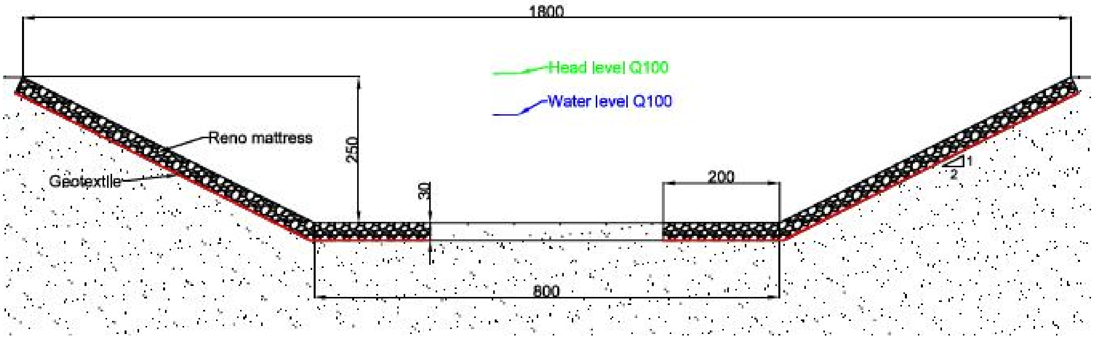


Figure 128 Typical trapezoidal cross section – Q100 = 80 m3/s – Lengths in cm

Computed velocities for the trapezoidal cross section are 3.7 m/s, Reno mattresses protections could fit for this kind of structure.
In case of a rectangular cross section, excavations are to be made with the following dimensions: width = 12m, depth = 2.5m. No protections needed.

9.5.3.2 Bridge

The project involves the demolition and reconstruction of four bridges. These structures are the similar, only the width and span may change.
Several types of bridges can be imagined, but keep in mind that it is preferable to avoid any contact with the water. According to the skills of the local construction companies, the following structures can be implemented:

- Ø Composite steel beam Bridge: quite easy to build, it provides enough span to avoid piers in the river bed. The obtained deck is thin compared to other technologies.

Figure 129 Example of a 19m-span composite steel bridge

- Culverts: two 5x2.5 m box culverts can be built. This is the economic way to implement hydraulic structures in a river (prefabricated structures).

Figure 130: 5 x 2.5m culvert

- Concrete Slab Bridge: such structures can be made in Rwanda but will require one or two piers in the river bed.

Figure 131: 15m span slab bridge on Sebeya river

9.5.4 Nota Bene

These works, giving their important area, are very expensive. A detailed study would have to determine whether or not the bank protections are needed everywhere. For instance, channel protections could be implemented only in curves or when crossing urban areas.

9.6 ID – 5 Susa and Muhe Rivers Bridge resizing

9.6.1 Location

Hydraulic structures crossing the road to Gisenyi have been overtopped several times the last years. The most problematic structure is the one over river Muhe because it generates large overflows in Musanze urban area. This structure is also damaged so it is a priority to engage fixing works.

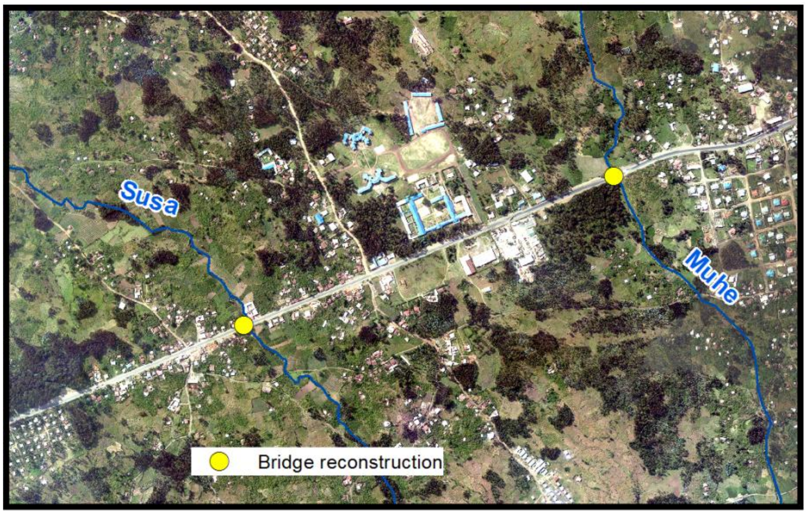


Figure 132 Muhe and Susa's hydraulic structures

The current structures specifications are detailed below. The capacities have been computed thanks to the software HEC-RAS.

Table 14 : Hydraulic specifications for Muhe and Susa structures

	Susa	Muhe
Structures	box culvert (height = 2.9m, width = 3m)	2 x 1000 mm concrete pipes + 1 x 2500mm corrugated pipe
Capacity before submergence (m^3/s)	25	15
Estimated Q100 (m^3/s)	77	44

9.6.2 Specifications

9.6.2.1 Muhe River

This structure is made of several small ones: they should be replaced by a unique larger one. Moreover, space is limited within a bed width of 12m.
Proposed works are as follow:

- Current bridge is to be removed and an excavation has to be done at the level of the former corrugated pipe (approximately 3.75m under the top of the current deck);
- Remove the small weir right upstream the current bridge and reshape smoothly the slope of the upstream river bed (over 8 to 10m). This has to be made with a concrete floor as it is nowadays;
- Distance between abutments= bridge width = 12m;
- Upstream clearance = 3m;
- The bridge can be made using composite steel beam technique (unique span, thinner deck). Deck elevation is unchanged.

The capacity of such a bridge is about 80 m^3/s. The bridge offers a clearance of 70cm for the 100y flood (44 m^3/s).

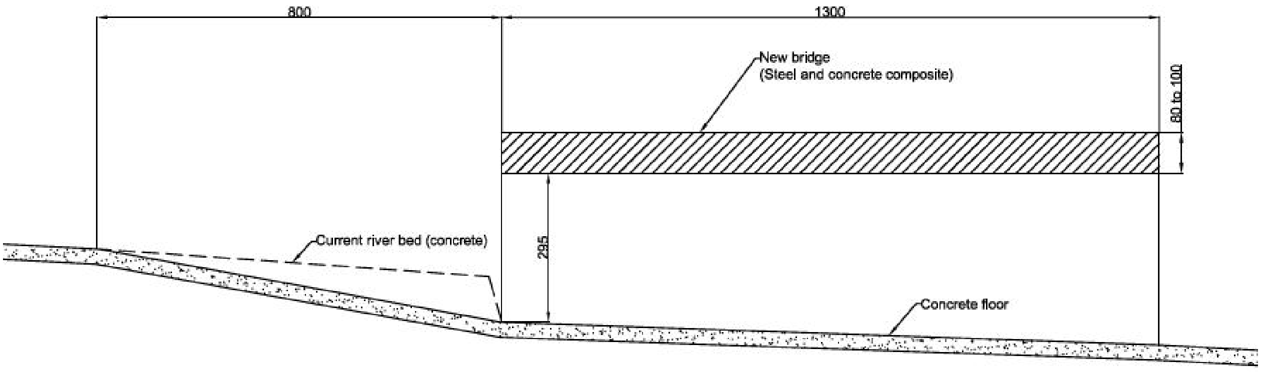


Figure 133 Longitudinal profile of the Muhe river proposed new bridge (lenths in cm)

9.6.2.2 Susa River

This hydraulic structure is also insufficient when floods occur but causes less damages around due to the lower density of houses. Resizing this structure is not a priority yet but will certainly be soon necessary because of the Musanze city growth.

Enough space is available around the Susa River so the structure enlargement can be done by simply building an additional structure right bank.

Proposed works are the following ones:

- Keep the existing culvert;
- Excavate right bank, upstream and downstream the road up to the current bed level;
- Fill left bank, upstream of the road, next to the building in order to smoothly reshape the curve (current culvert entrance is very sharp);
- The previous “cut and fill” operations have to reshape the curve of the Susa river in order to un-skew the channel.
- Build an additional to the right of the existing one. An identical one is enough to increase the capacity up to 46 m^3/s.

If culverts are built close enough to each other, central wingwalls will have to be removed.

9.7 ID 6 – Mutobo levee near WASAC plant

9.7.1 Location

Wasac plant is threatened by Mutobo River when floods occur. The plant can be protected along small linear thanks to a levee.
This will not only protect the water plant but also the houses located south of it.

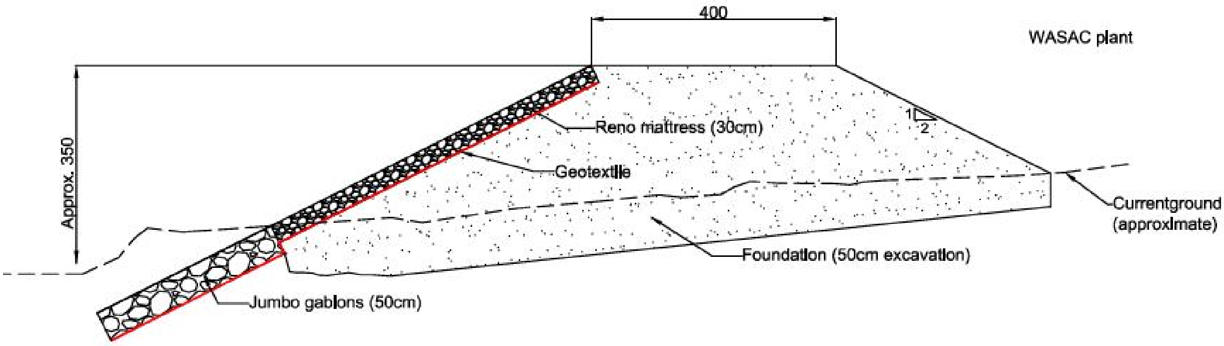
Figure 134 Location of the projected dyke

9.7.2 Specifications

Considering a Q100 protection (Q = 35 m^3/s), the levee specifications are the following ones:

- Ø 120 m in length;
- Ø Between 1.5 and 2.5m high (if it is built along the existing fence);
- Ø The road has to be elevated to the same elevation than the crest of the levee.

The typical cross section is displayed below.



9.8 ID 7 – Murufrwe: rebuild houses on road-levelled embankments

9.8.1 Location

The national road between Musanze and Gisenyi creates a kind of dam and blocks the spilled water from Murufurwe river. A lake then appears and floods several houses. Some of them are destroyed.
Drainage could be improved in this area but would worsen the situation downstream for the people living next to the endorheic area and that are already flooded.

Figure 135: Location of the concerned houses

9.8.2 Specifications

This measure is easy to implement: people whose houses have been destroyed and who cannot be relocated elsewhere can rebuild their houses on an embankment elevated at the same level of the road. The embankments heights vary from 2 to 5 meters.

9.9 ID 8 – Levee along Rungu River

9.9.1 Location

The campus of the University of Rwanda is located right bank of Rungu river. It is threatened by spilling water, especially upstream of it, in a curve. This curve is not natural and the river has probably been detoured while constructing the campus. Overflows may happen and water could reuse the former river bed through the buildings.
A levee could be built right bank to protect the University from flooding.

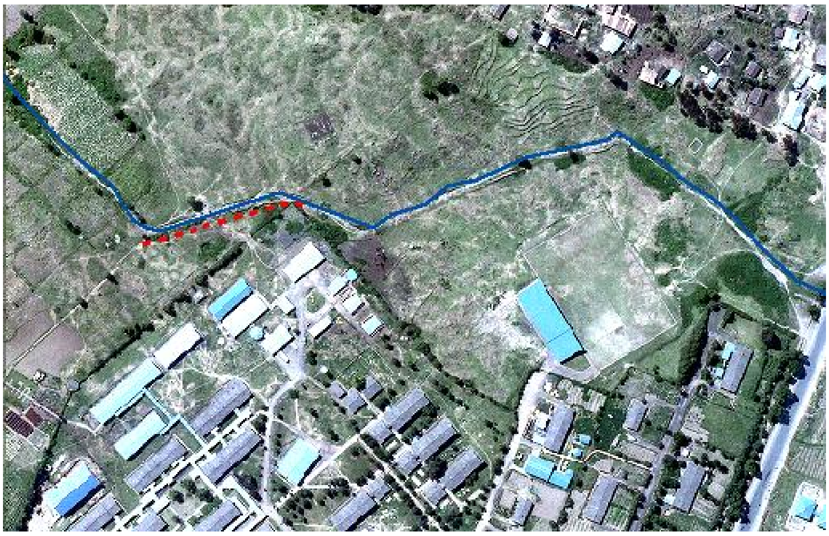


Figure 136 Location of the suggested levee

9.9.2 Specifications

Local slope of the river is 5.5% and the 100y discharge is 29 m^3/s. This event should be considered as design criteria: an overflowing levee can be more disastrous than if no levee at all.
Main characteristics of the levee:

- 4m width crest;

- 2/1 slope;
- Reno mattress (0.3m thick, rockfill size = 100/150mm).upstream to protect the structure against erosion (velocities = 3.1m/s)
- Excavation of 50 cm right under the structure.
- Height of approximately 2m (to be precisely estimated with accurate topography).

Levee is to be built approximately 4m away from the right bank in order to reduce the risks of erosion.

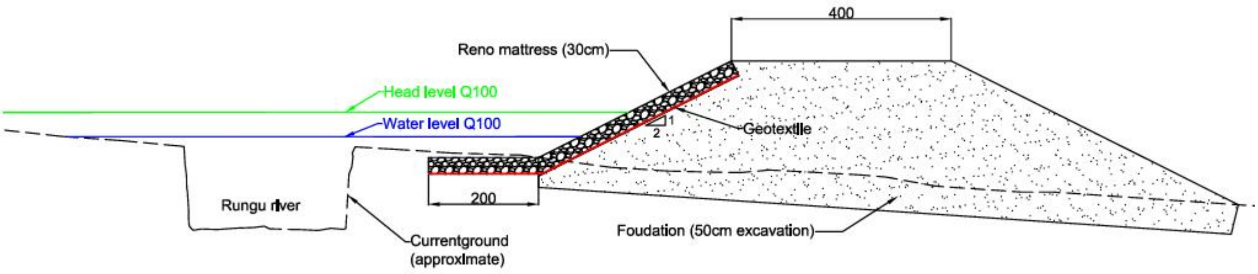


Figure 137 Typical cross section on Rungu's Levee near University

9.10 ID 9 – Sebeya diversion channel

9.10.1 Location

The town of Mahoko is regularly flooded by Sebeya River. Overflows occur in the town centre because the channel capacity is insufficient when the discharge reaches 40 m^3/s.
The solution presented in this chapter describes a “diversion channel”, dug parallel to the Sebeya River and which purpose is to evacuate excess water from the Sebeya before it enters the town of Mahoko. Excess water will be sent to a former river bed left overbank. These works are inspired by what already happens when water spills.
Total length of the channel is 1.4 km. Weirs will have to be built at slope breaks to avoid erosion.
The map below shows an aerial view of the project.

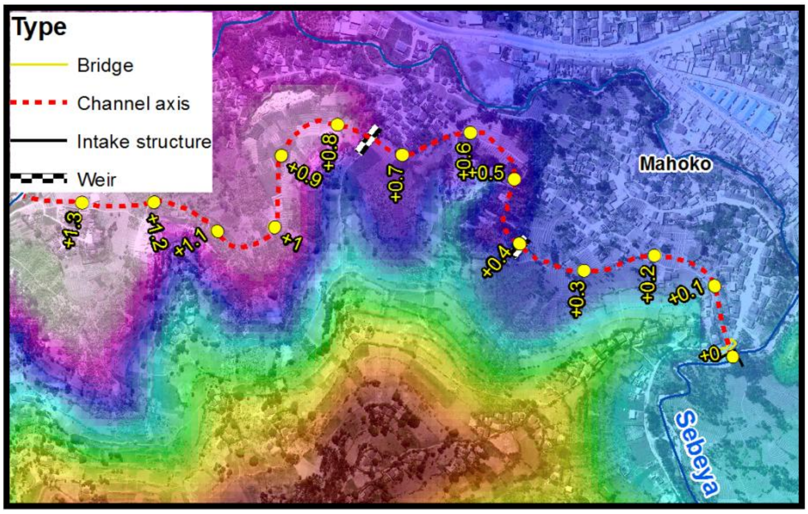


Figure 138 Mahoko diversion channel

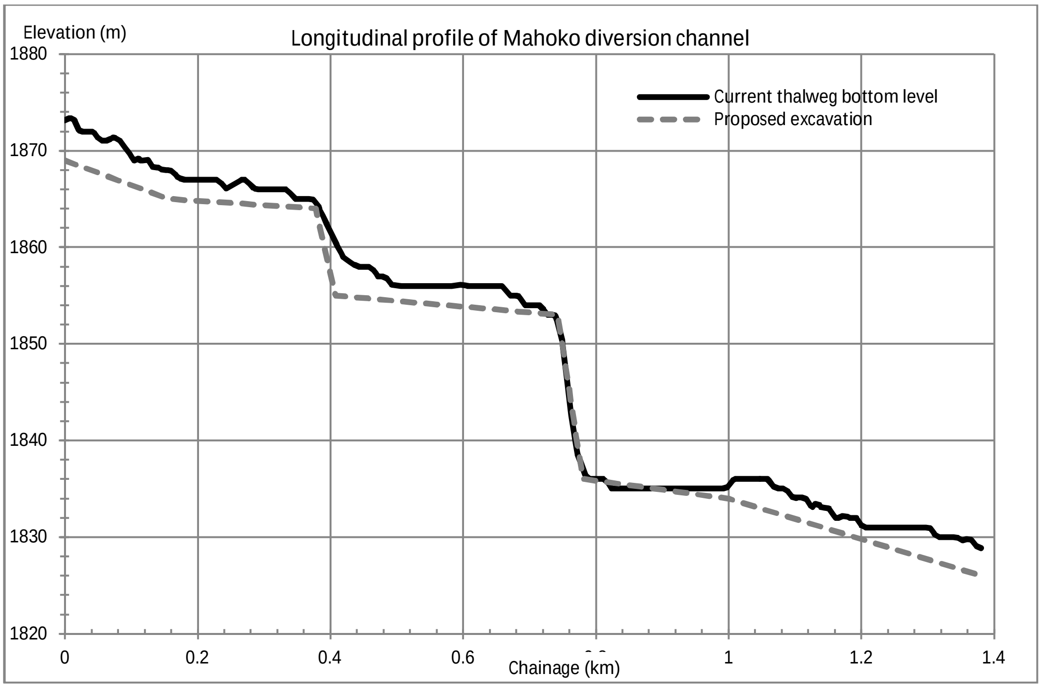


Figure 139 Longitudinal profile of mahoko diversion channel

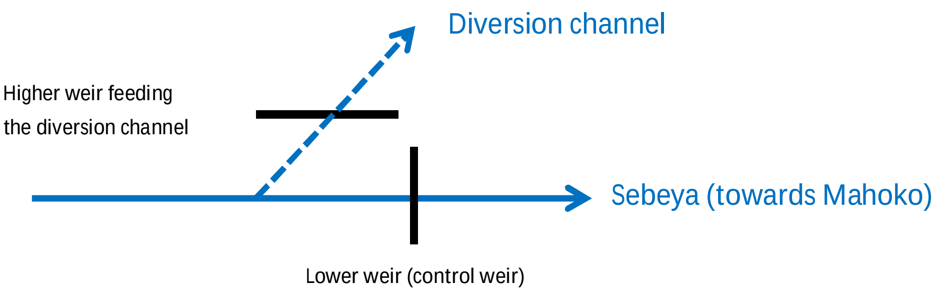
The estimated 100y flood in Mahoko is **74 m³/s**. The diversion channel maximum capacity has been limited to 25 m³/s for technical reasons (see next paragraph "Specifications"). The theoretical protection level is approximately 65 m³/s, very close to the 100y flood.

9.10.2 Specifications

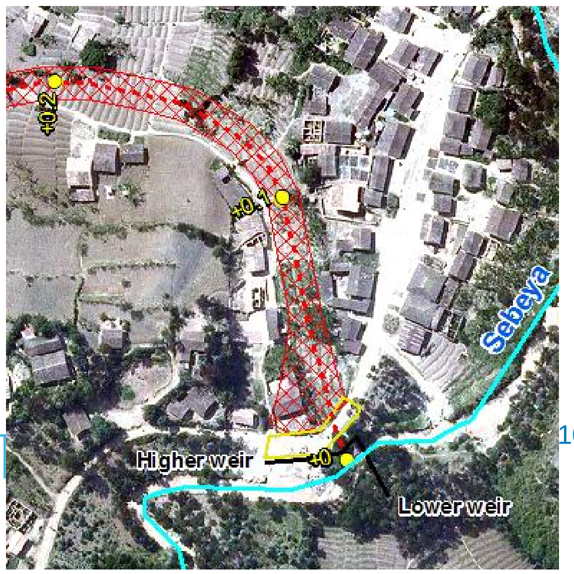
9.10.2.1 Intake structure

Intake structure consists in two weirs built at different elevations.

- A lower weir (control weir) on which Sebeya River spills;
- A Higher weir which feed the diversion channel when a flood occurs.



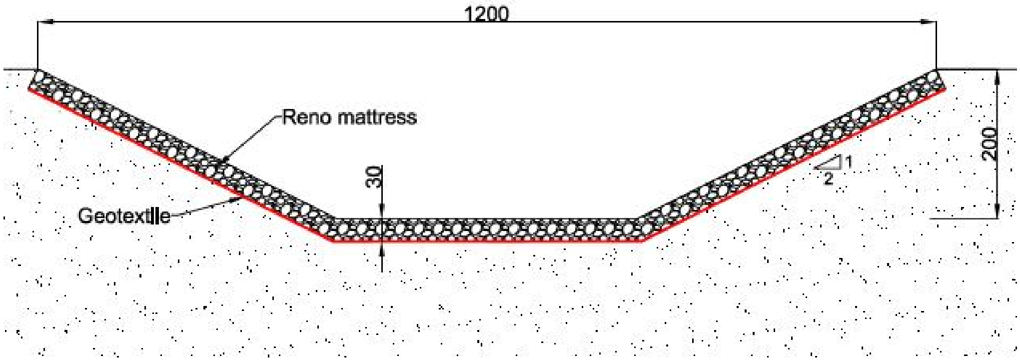
Both of these weirs have to be dimensioned to let pass 40 m³/s at maximum towards Mahoko. That means the higher weir (diversion channel) has to start spilling for a lower discharge than 40 m³/s to take into account the probable continuing increase of the water level (generating more discharge in Sebeya channel as well).
The higher weir's location is right on an existing road: if built, the weir will have to be crossed by a bridge.



9.10.2.2 Diversion channel

The dimension of this channel is limited because of nearby houses in Mahoko. The width of the channel shall not excess 12 meters or families' relocations would be necessary.
The red hatches on the right map a 12 meters wide buffer centered on the channel axis.

The typical cross section of the channel is the following one:



These are the main specifications of the cross section:

- Maximum admissible discharge = 25 m^3/s (head level to the edges);
- Velocities vary from 1.9 to 3.1 m/s, depending on the slopes;
- 2/1 slope;
- Reno mattresses protections can be implemented (0.3m thick, rockfill size = 100/150mm).

9.10.2.3 Weirs

Two weirs have to be built on the diversion channel because of two important slope breaks. The first drop is 9m high (Km +0.4) and the second one is 20m (Km +0.75).
Before advising particular structure for weirs, a soil investigation has to be performed to estimate how close the bedrock is. Indeed, a simple soil stripping could be implemented in order to use bedrock as natural protection.

Figure 140: Gabion boxes weir (left) / Natural bedrock fall on Susa River (right)

9.11 ID 10 – River training on Sebeya River near “Petit séminaire de Nyundo”

9.11.1 Location

“Petit séminaire” of Nyundo has been severely flooded due overflow from Sebeya river. The river bed is not wide enough.
The proposed solution is to enlarge the river bed to decrease the frequency of overflows.

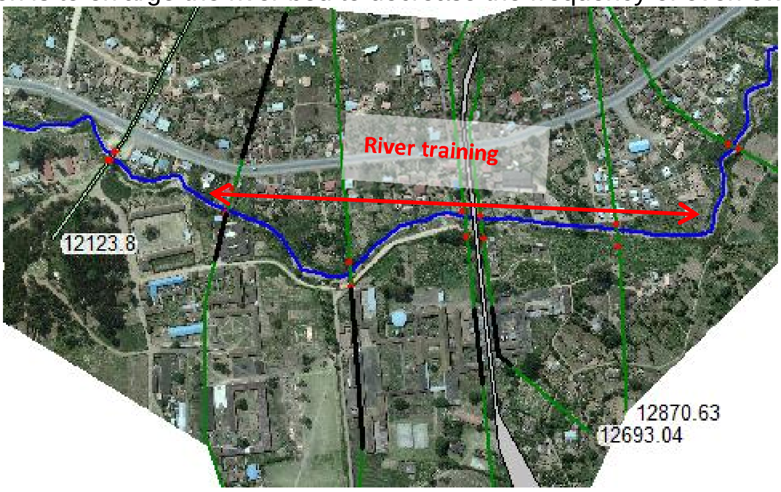


Figure 141 Proposed river training (HEC RAS cross sections in green)

9.11.2 Specifications

The enlargement of the river bed has to be done by keeping a berm into the main channel. Indeed, to avoid too many changes in sediment transport, the channel has to be unchanged for frequent floods that shape the river bed.

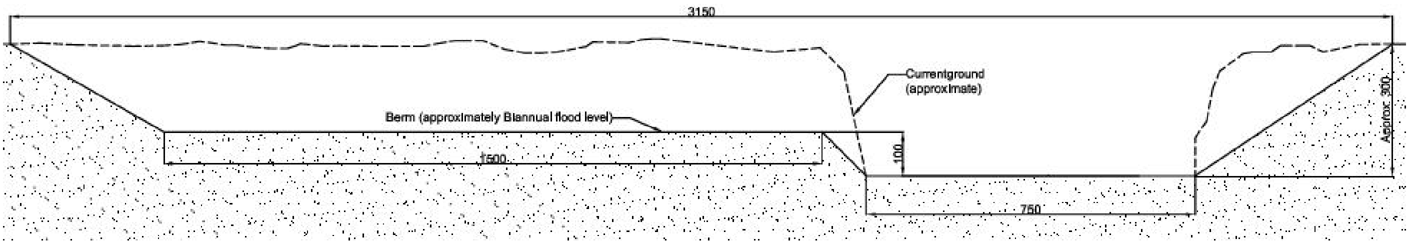


Figure 142 Typical cross section for river training

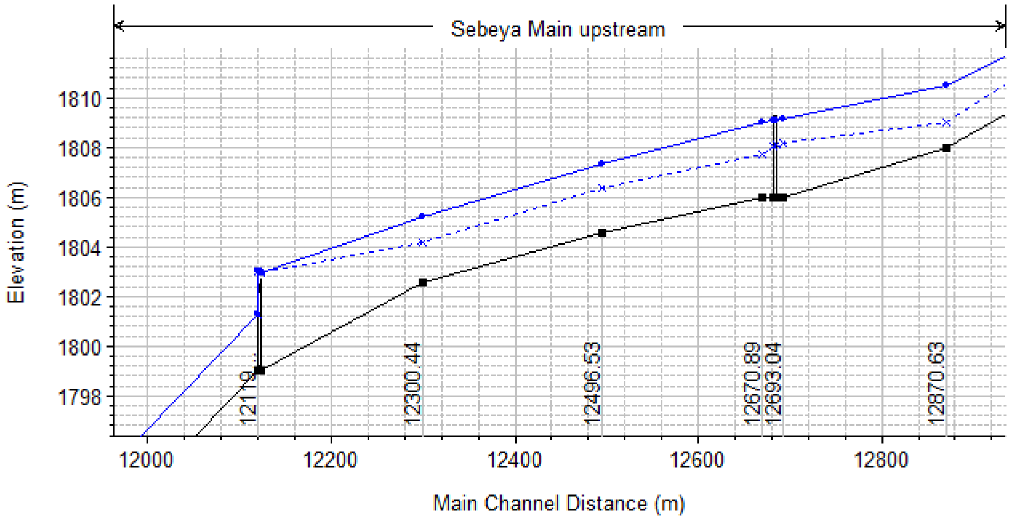


Figure 143 Impacts on the water levels in the sector of Nyundo

The bridge enabling access to "petit séminaire" will also have to be widened to a 15m span. Such bridges can be easily implemented (see for instance the one in Gihira, Figure 131).

Computed velocities vary from 2 to 3m/s, protections should be added on the banks (vegetal protections or Reno mattresses).

9.12 ID 11 – Right bank protection on Gisunyu Gully

9.12.1 Location

At the confluence of Karambo river and Gisunyu Gully, left bank is severely damage by floods (erosion). The bridge crossing Gisunyu has been damaged: right abutment has been scoured and the structure is threatened.

Figure 144 Aerial view of the vicinities of confluence between Ginsunyu and Karambo

Figure 145 Scoured abutment (right bank)

Overflows occur right over bank (see the red arrow in Figure 144), downstream of Gisuyu Bridge. These overflows may not happen anymore because of the newly built diversion channel enabling a large quantity of water from the two streams to reach the Sebeya River via another channel. This diversion channel is almost as large as the Karambo River.

9.12.1 Specifications

The top-priority is to fix the bridge.
An excavation has to be made until reaching the bed rock if close to the current bed level. The first decayed 50cm of the bedrock shall be removed to reach the proper layer.
Reinforced concrete has to be poured into a concrete form to recreate the disappeared abutment.
This can also be done with masonry techniques.

9.13 ID 12 – Location and stopping of new forming gullies

Due to landuse change and runoff increase, some gullies recently appeared at the bottom of thalwegs where no specific riverbed used to exist. As soon as a new riverbed appears a vicious cycle is born: runoff concentrates and deepens this same river bed draining actually more water. If detected soon enough, this phenomenon can be stopped with affordable means.

9.13.1 Location

Such phenomena can be observed in Shingiro sector and also on the Nyabitondore River where the stream has been detoured without any precaution. Not all the streams have been seen during the site visits so it would be essential to involve local population in querying the different concerned sites.

Figure 146: Example of forming gully, Shingiro sector

9.13.2 Specifications

Once located, the concerned gullies can be treated by implementing barriers in the most affected parts. These barriers can be in wood or in stones depending on the size of the gully and the importance of expected runoff. Preferably they will be done all along the channels from upwards to downwards as the phenomenon starts in the hills and progress in the valleys becoming bigger and bigger, deeper and deeper.
These structures accumulate sediments in terraces and these ones must be revegetalized and preferably exploited to produce fodder or for other purposes. Pennissetum and bamboos are good options to promote. This has been tested successfully in some countries and can be extended to Rwanda.

9.14 ID 13 – Agricultural practices

Modifying the agricultural practices aiming at a more "soil-friendly" way of cultivating should be implemented in the catchment. Indeed, low-cost measures can easily be done and would therefore cover a large area.
Soil erosion and water infiltration depends on five factors which are:

- Climate index, characteristic of each location as a consequence of its climate
- Soil erodibility index, which depends on its main properties (texture, structure, organic matter, permeability)
- Slope index
- Cover crop index which is generally experimentally established
- Erosion control index which considers the implementation of erosion control practices

The techniques used to control erosion and water infiltration are based on these factors, the rationale being to reduce each of them at its minimum. Unfortunately, some of them (climate index and soil erodibility) are difficult to control. Climate is considered as the main accelerating factor.

Erosion control techniques are therefore oriented towards minimizing slope and crop indexes.

Radical terracing is very efficient but very costly, it generally reduces fertility for 3 to 5 years (need of fertility regeneration by large amount of manure – livestock) and can induce landslides in schist soils in particular.
Crop index is by far the most interesting factor in erosion control. It is cost effective and ensure fertility improvement.
Techniques for sheet and rill erosion control are:

- Reforestation and rill erosion control

Ø This technique is generally the one proposed when slopes are of 40% or more. It is recommended to use species of interest for farmers and for the general economy (fire wood, craft wood etc.).

Ø It is very efficient (advantage) but farmers are not interested as they consider that reforested areas as unused lands for grazing and other traditional activities.

- Contour ditches

  Ø This technique has been widely promoted in Rwanda and is traditionally associated to erosion control. Its role is to reduce the length of the slope. Its efficiency is little as it contributes to reduce erosion only by around 40% if applied alone. It is also high labour consuming to put in place (more than 100 md/ha) and to maintain regularly. It reduces agriculture land up to 15-20%. In addition, it has no or little positive impact on soil productivity improvement.

- Live hedges

  Ø These curves are generally planted with pure or mixed live hedges (pennisetum, callyandra, leucaena…) with increased efficiency (soil soles reduced by 90%, even more). This technique is particularly interesting when associated with livestock being used as fodder production. It is also recommended for nitrogen fixing in soils when using legume trees (Leucaena, Calliandra, Gliricidia, Sesbania,…).

- Agroforestry practices

  Ø Hedge rows from the previous paragraph can be considered as agroforestry. The species used are supposed to have multiple uses (fodder, tutors for climbing crops, fire wood, nitrogen fixing trees, etc.). Agroforestry also uses big trees (Grevilea, Cerdella…). They reduce rainfall velocity and its negative impact on the soil. They produce some very useful biomass for feeding cattle, for mulch or for compost. Depending on the number of trees per hectare and other associated techniques (e.g. hedge rows), erosion can be reduced by more than 200%.

- Mulching and cover crops

  Ø Mulching is by far one of the most efficient erosion control technique.

- Intercropping

  Ø Intercropping consists in mixing crops (association of up to 5 crops in the Rwandan farming systems).

- Techniques for gully erosion control

  Ø See chapter 9.13

Feasibility study and detail design have been performed on Sebeya catchment[6].

We have seen an example of what is possible to do, on the slope of Muhabura mountain.

[6] Feasibility study and detail design of the Early Implementation Project on Sebaya and Upper Nyabarongo Catchment (Integrated Water Resources Management Programme Rwanda - May 2016) – Ref. 201501033.062

Figure 147: Example of stone-made fences: could be better rearranged to reduce runoff

9.15 ID 14 – Implementation of early warning systems

Warning systems are usually based on three kinds of data:

- Ø Weather forecasts;
- Ø Rainfall gauges or radar;
- Ø River gauges.

Weather forecast: lack of accuracy on the area due to local and random distribution of storms.

Rainfall analysis: due to the local distribution of the rainfalls in Rwanda, implementing warning system based on rain gauges would not be efficient and could be risky because:

- o the rain gauges density is currently to low: storms might not be detected;
  - Ø In 1965, Jean Rodier[7], after several tens of studies in Afrika, concluded that, for convective tropical storm, it is possible to obtain a good rainfall estimation if the density of rain gauges is as follows[8]:
    - 6 rain gauges for 5 km² catchment
    - 12 rain gauges for 15 km² catchment
    - 18 rain gauges for 50 km² catchment
    - 22 rain gauges for 100 km² catchment

    This information can be found in scientific article (discussions at the end) at the following internet address:

    http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.540.864&rep=rep1&type=pdf
  - Ø
- o increasing the density of gauges is not reasonable technically and financially;

The best remaining solution for rainfall analysis would be the radar data (live measurement of rainfall intensity in a range of 100km or more) but this solution is out of reach for the project.

River analysis: River gauging upstream of inhabited areas remains the best solution to warn people in that case. The counterpart of it is the lack of time between the warning and the upcoming danger: the flood is not anticipated but witnessed.

[7] Pioneer and father of tropical hydrology at ORSTOM

[8] « La traversée de la pluie et l'hydro climatologie » - Guy Bédiot – Editions Johanet – p112-113

9.16 ID 15 – Water storage

An obvious solution to reduce floods would be to store water upstream of the inhabited areas. Unfortunately, this solution **is not suitable for the studied areas because the high steepness of the streams and their beds' lack of deepness considerably limit the available volume for storage.**

The following example related to Muhe River at the Kinigi's bridge (15 km²) illustrates this assertion:

- Estimated discharge for 2014's flood is between 50 to 70 m^3/s (Return period between 5 and 30 years – see hydrological study).
- Time of concentration (Tc) is computed between 50 mn and 120 mn according to the formulae used (Kirpich, Passini).
- Considering that basic time (Tb) is close to 2xTc we obtain the following roughly estimated hydrograph :

Figure 148: Natural hydrographs of Muhe River flood

The volumes are then about 150 000 m^3 and 500 000 m^3.

- To divide the peak discharge by 2 thanks to a dam and a reservoir, we had to obtain these hydrographs :

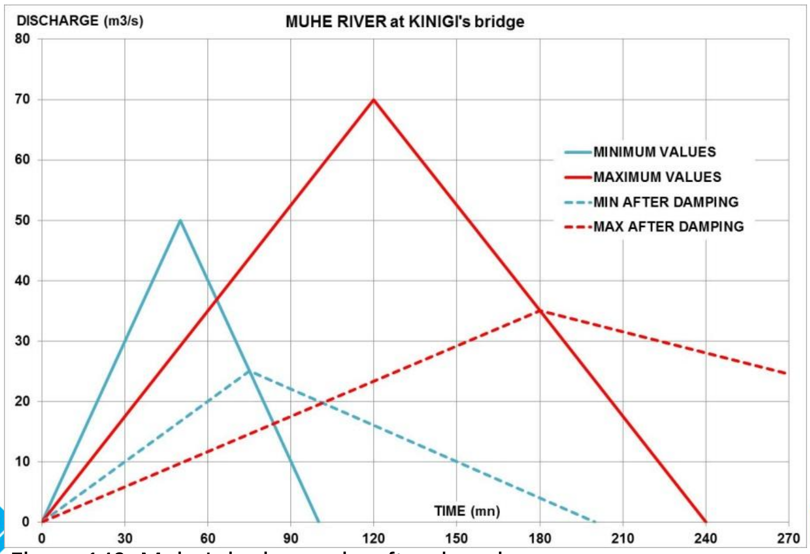


Figure 149: Muhe's hydrographs after damping

Volumes which need to be stored are respectively about 75 000 m^3 and 250 000 m^3.

- With a constant depth of 5 m (which is a lot), the surface of the reservoir must be respectively 3 and 10 ha.

These results show that it is not an available solution.

Nevertheless, on the endorheic areas, such as Murufurwe River, near the road NR2, it is important, for downstream inhabitants, to keep unchanged the retaining capacity of the area upstream the road.

9.17 ID 16 – Reducing water velocity

It is interesting and feasible to reduce water velocity as far as the water is not concentrated in river bed. It is the principle of reforestation and improving agricultural practises.
When the water is concentrated in the riverbed, it becomes imaginary to want to slow down it, because of the high slopes.
Flow regime is near critical one and speed depends only on the width of the river bed.
It is only for rivers with low slope that it is possible to reduce the speed of flood waves by forcing overflowing on flood prone areas and storing a big part of the volume of the floods.

Annex 1. ToR for overall study

Kingdom of the Netherlands IWRM Programme Rwanda

Terms of Reference
Special IWRM Study: Flood management volcanoes area

Objective:	Support the IWRM Department in managing flood risks
Position(s):	International short term Flood Management specialist
Profile:	The specialist(s) to be hired for this study will comprise the following expertise: hydrometeorology, hydrological modelling, geology, basic design flood control infrastructure.
Input:	66 working days jointly, maximum (in Rwanda), over a timeframe of maximum five calendar months from start date
Mission planning:	May – September 2016

Relevant Background

The IWRM Programme, funded by the Government of The Netherlands through the Royal Netherlands' Embassy in Kigali, supports the Rwanda Natural Resources Authority (RNRA) of the Ministry of Natural Resources in order to enhance capacities at national, catchment, and local (district) level with regard to catchment management and IWRM. In this framework, several studies will be implemented, to support the IWRM Department in particular, and the Government of Rwanda at large, in managing specific IWRM issues, or to support the development of catchment plans for the demonstration catchments of the programme.

This study focuses on the specific issues of flooding in the volcanoes area.

Introduction to the study

The hydrological system of Rwanda is sub-divided into two major basins (Nile basin covering 67% of the country's territory and Congo basin covering 33%) and nine level one catchments as illustrated in the following map.

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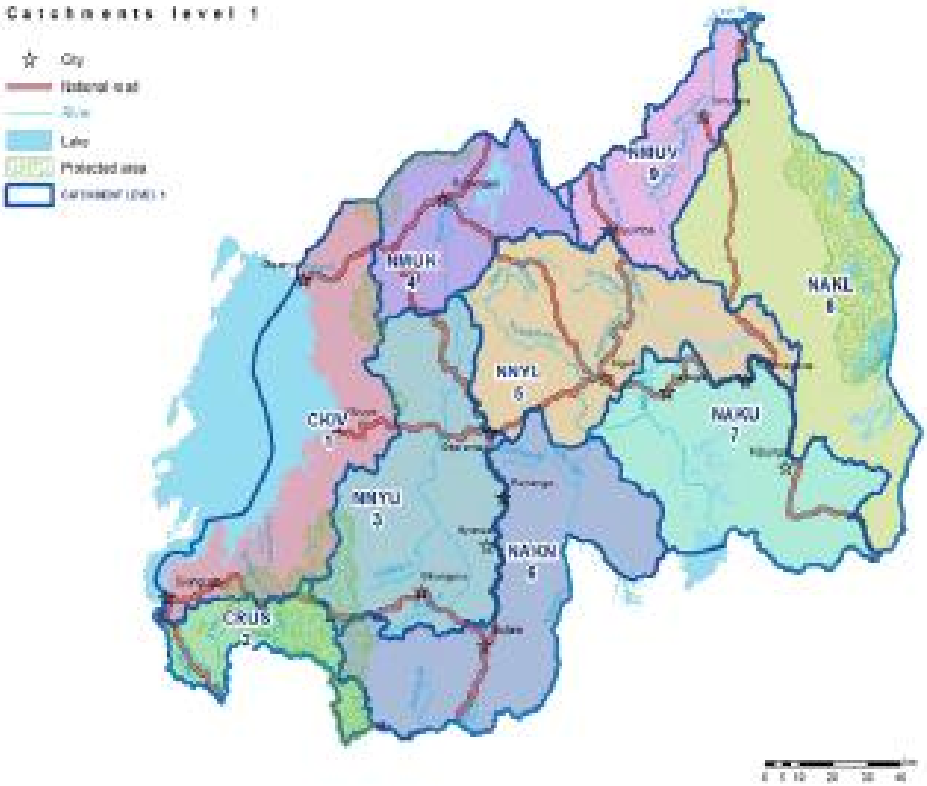

In the above map, the initials:

1. CKIV stands for Congo Kivu Catchment
2. CRUS stands for Congo Rusizi catchment
3. NNYU stands for Nile Nyabarongo upper catchment
4. NMUK stands for Nile Mukungwa catchment
5. NNYL stands for Nile Nyabarongo lower catchment
6. NAKN stands for Nile Akanyaru catchment
7. NAKU stands for Nile Akagera upper catchment
8. NAKL stands for Nile Akagera Lower catchment
9. NMUV stands for Nile Muvumba catchment

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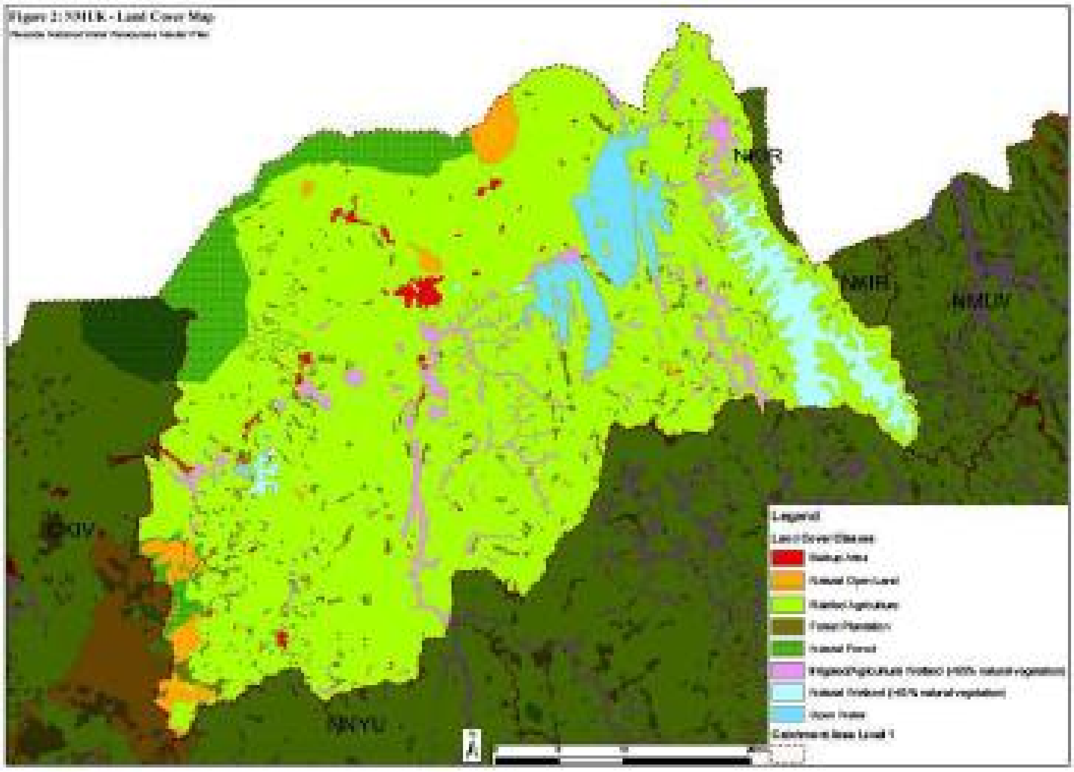

One of the major challenges being faced in these catchments is related to flooding issues. This flooding is particularly prominent in the Northern Province, especially in Musanze, Nyabihu and Rubavu Districts located in Mukungwa catchment and the north part of the Kivu catchment in the lava region.

This flooding issue is a serious threat to many infrastructures such as schools, factories, commercial centers, erected downstream of these catchments, to cropped lands, as well as to human lives.

Some years ago, the main road Kigali-Rubavu has been destroyed by floods and the government invested a huge amount of money to reconstruct key infrastructure of road and bridges.

In order to address the issue of flooding, mainly for the sustainability of the infrastructures located in the downstream part of the Mukungwa catchment, the Government of Rwanda through MINIRENA has tried to mitigate that issue by putting in place gabions in three main gullies / tributaries, conveying water from the upstream volcanoes area down to the main river. These are the main water courses that pose a flooding threat to the city of Musanze. The gabions subsequently failed following a flood event. In addition to this, the national road between Kigali and Rubavu has been reinforced upon flood induced damage.

In line with the Rwanda National Policy for water resources management and its strategic implementation plan, the Government of Rwanda intends to rehabilitate the entire Mukungwa

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catchment, which has a total area of 1,902 km2, of which 119 km2 are covered by the Volcanoes National Park.

In this connection, the Ministry of Natural Resources through the Rwanda Natural Resources Authority intends to carry out, with support of the IWRM Programme, an assessment within the catchments in the volcanic area to identify the areas contributing the most to flood production and propose the mitigation measures and activities to be carried out in the catchments, so that the rehabilitation efforts can start from there and cover the entire lava region progressively.

Rationale for the study

One of the major challenge being faced by water resources in Rwanda is related to floods, which results from improper management of the catchments, leading to high soil erosion and increase in surface flow in detriment of ground water recharge enhancement. As the flood waters derive mainly from the upstream volcanoes, a source based approach is a good starting point for reducing flood risks. Downstream mitigation measures may further complement an integrated flood risk management solution.

The most affected sectors are Kinigi, Muhoza, Musanze, Kimonyi, Nkotsi, Gataraga and Busogo of Musanze District, as well as Mukamira Sector of Nyabihu District, and the northern sectors in Rubavu District.

Addressing the issue of floods may require a combination of measures. As this area is known as one with high rainfall (more than 1300 mm/year) it is a big need to conduct a deep analysis of quantity of water which can be expected in the area.

Study objective

The purpose of the study is to contribute to reduction of flood risks and mitigation of impacts of flooding in the most affected downstream areas in the lava region.

The main objective of the study is to come up with a concise integrated plan for flood risk management in the area. The plan may include upstream measures to reduce or delay discharges, hydrological measures at key bottlenecks to allow for easier conveyance of water to reduce local flooding (e.g. at intersections with roads), and downstream measures to reduce impacts, such as zoning plans for land use and habitation.

Scope of Work / methodology

The scope of the current assignment is as follows:

1. Assess the available study results of a flood risk study of the same area, implemented by INES (Report available: A Baseline Survey of the Hydrological Systems in the Greater Virunga Landscape around the Volcanoes National Park (PNV))
2. Subject to the assessment, the following points may be adapted to avoid repetition of work
3. Analyze available meteorological data of Busogo and Musanze stations, to obtain representative estimates of extreme rainfall events of different return periods

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4. Map the catchment areas (using GIS), including digital elevation model, land cover, land use, and geological data as far as available
5. Analyze hydro-meteorological characteristics / rainfall-runoff characteristics using applicable model (to be specified by the expert, based on data availability and fit for purpose);
6. Interview local authorities and communities to assess cycles and behavior of floods;
7. Develop flood maps (flood prone area, flood extent and depth) and summarize information on current impacts based on existing data sources (MIDIMAR, districts);
8. Collect information on different flood management interventions done in the past years;
9. Suggest sustainable flood risk reduction measures, including upstream and downstream prevention and mitigation measures;
10. Validate the results by means of site visits to selected sites and a validation workshop with local experts and district staff.
11. Provide training (formal and/or on the job, as per relevance and effectiveness) to RNRA staff and partner agencies, to enhance capacities of the Government of Rwanda to manage flood risks.

Main deliverables

The main deliverables of the mission, which shall be submitted to the Team Leader, are as follows:

Deliverable	Description
Technical Report	A complete report which includes the results of the study and recommendations will be delivered. The results and recommendations are to be presented at a workshop at the end of the study assignment. The draft final technical report shall be submitted to the team leader at least three working days before the end of the study assignment.
Technical files	Softcopies of maps, excel files, and models (subject to license and necessity) will be handed over to the RNRA and the ISU.
Mission Report	Concise report covering the activities and findings from each mission, and planning for follow up activities
Timesheet	The expert(s) will fill out a timesheet with concise description of his/her activities, using the project's timesheet template. The timesheet needs to be approved by the Team Leader.

Interactions with team members

The international expert(s) will collaborate closely with the RNRA staff, the ISU core team, and with other RNRA or project experts as and when needed.

Data sources

RNRA experts will assist the expert with all relevant existing information from MINIRENA and other ministries for the current assignment.

Mott MacDonald SHER SNV

Annex 2. Detailed scope of work for missions 2 and 3

Study objective:

In line with the Rwanda National Policy for water resources management and its strategic implementation plan, the Government of Rwanda intends to rehabilitate the entire Mukungwa catchment, which has a total area of 1,902 km², of which 119 km² are covered by the Volcanoes National Park.

Therefore, the Ministry of Natural Resources through the Rwanda Natural Resources Authority intends to carry out, with support of the IWRM Programme, an assessment within the catchments in the volcanic area to identify the areas contributing the most to flood production and propose the mitigation measures and activities to be carried out in the catchments, so that the rehabilitation efforts can start from there and cover the entire lava region progressively.

The purpose of the study is to contribute to reduction of flood risks and mitigation of impacts of flooding in the most affected downstream areas in the lava region.

The main objective of the study is to come up with a concise integrated plan for flood risk management in the area. The plan may include upstream measures to reduce or delay discharges, hydrological measures at key bottlenecks to allow for easier conveyance of water to reduce local flooding (e.g. at intersections with roads), and downstream measures to reduce impacts, such as zoning plans for land use and habitation.

A first mission has been undertaken from the 19th to the 30th of May and has carried out:

- An assessment of the available study results of a flood risk study of the same area, implemented by INES (Report available: A Baseline Survey of the Hydrological Systems in the Greater Virunga Landscape around the Volcanoes National Park (PNV)) ;
- An analyze of the available meteorological data of Busogo and Musanze stations, to obtain representative estimates of extreme rainfall events of different return periods;
- A mapping of the catchment areas (using GIS), including digital elevation model, land cover, land use, and geological data as far as available;
- An Analyze of the hydro-meteorological characteristics / rainfall-runoff characteristics using applicable model (to be specified by the expert, based on data availability and fit for purpose);
- Interviews with local authorities and communities to assess cycles and behavior of floods;
- First recommendations of flood risk reduction measures ;
- Suggestions and program for the following steps of the study.

Regarding the quality of the DEM available and the specificities of the field, flood mapping could not been performed.

The scope of the next steps should be:

- To develop flood maps (flood prone area, flood extent, depth);
- To propose flood management plan.

Methodology

The methodology depends on the configuration of the field.
Different procedures for the different situations encountered can be undertaken.

1. Rebeya, Muhe and Susa rivers

All the field survey will be investigated by walking as it is not accessible by car.
The scope of this phase is as follows (mission type 1):

- interview of the people living near the rivers and possibly submitted to flood in order to know:
    - Which flood do they remember?
    - What was the level reached during these floods?
    - What do they do in case of flood?
- Measurement of the cross section near the house;
- Estimation of roughness of the bed ;
- Measurement of the possible existing structures having influence on the flows as culvert, weir, bridge, …
- Estimation of the return period of each events matched by an interval of uncertainty;
- Hydraulic modeling of the river bed and computation => determination of discharges in accordance with the heights observed ;
- Transformation of these discharge in reduced discharge;
- Put back these values on a graph of Gumbel compared with rains;
- Define characteristic reduced discharges thanks to a fit line which crosses all the rectangles of uncertainty;
- Hydraulic modeling of the 100 years return period discharges;
- Mapping of the flood prone area;
- Flood risk reduction measures recommendation.

2. Mukadama, Murufurwe, Rungu, Nyabitondore, Bikwi rivers

The scope of this step is as follows (mission type 2):
These rivers (and the one without name) will be analyzed as the previous one on the part included on the volcano slope.
The values of discharge obtained for the different events surveyed will complement the series of discharges-frequencies obtained on the previous catchments. The characteristic discharges will be defined.
On the downstream part, for the rivers which have no exit, it will be necessary to analyze the volume of the different hydrographs associated to the characteristic discharge (use of the time of concentration to build hydrographs with a triangular shape).
After these volumes known, it will be necessary to compute level of flows for the different discharges and with different hypothesis of capacity of the existing culverts. The results will give the risk of overflowing upstream the road.
In case of overflowing, hydraulic model will be built in order to appreciate, for each characteristic flood the storage capacity of the plain upstream the road and the discharge which remains downstream the road. These values of discharge downstream will be used to determine if there is flooding or not, downstream.
Flood mapping and Flood risk reduction measures recommendations will be produced thanks to these results.

3. Sebeya river

The scope of this step is as follows (mission type 3):

- Field investigations on the different strategic points (bridges, particular cross-sections…) spotted on maps (aerial photography…);
- Analysis on hydrographic stations in order to establish rating curves of better quality and to know discharges observed with less uncertainty ;
- Statistic analysis of the annual maximum values of peak discharge reviewed with a Gumbel law ;
- Rainfall-runoff modeling using different range value for the different coefficients used (runoff coefficient…). Different hypothesis will be done concerning distribution and extension of rainfall ;
- Comparison of the results, in term of characteristic discharge with the statistic results and the probabilistic formula established in 1992;
- Characteristic discharges assessment ;
- Hydraulic modeling with the DEM 10 and field investigations;
- Flood mapping of the 100 years return period floods;
- Flood risk reduction measures recommendation.

On the following sectors: **Bugushi, Busamana, Cyanyarwe, Rubavu**, there is no river registered. Analysis of SRTM 30 and DEM10 (partially missing) shows that there are some thalwegs. Field survey is necessary to see if there are flooding risks. If yes, mapping will be done as for the mission type 1.

Annex 3. References

[1] Cayla O. and J.P. Broch, (1992). - Probabilistic regional precipitation analysis. Proc. Hydropower'92, Broch et Lysne (eds), Balkema, Rotterdam, 389-394

[2] Cayla O. (1993). – Probabilistic calculation of design flood – SPEED. Proc. Int. Symposium on Engineering hydrology – San Francisco, July 25-30 1993, ASCE pp.647-652.

[3] CFGB (1994). – Les crues de projet des barrages : méthode du Gradex. Design Flood Determination by the Gradex Method. 18ème congrès CIGB-ICOLD Bulletin du comité français de grands barrages, n°2, November 1994, 7-96.

[4] Cayla O. (1995). – Probabilistic calculation of design floods and Inflows – SPEED; WaterPower 95 – ASCE – San Francisco, July 25-28 1995, pp. 2476-2486

[5] Cayla O. et J.C. Carré (2012). – Analyse probabiliste régionale de la pluviométrie extrême en France métropolitaine. *Evènements extrêmes fluviaux et maritimes, SHF - Paris*, 1-2 février 2012

[6] J.C. Carré (2013). Extreme peak discharge evaluation through a probabilistic approach: assessment of 20 years' experience by Artelia/Sogreah. Evènements extrêmes d'inondation, SHF – Lyon, 13-14 November 2013

[7] J.C Carré (2016) – Usefulness of a regional probabilistic approach to determining design discharges of hydropower plants in Albania – FLOODrisk 2016 conference – Lyon, 18 octobre 2016

[8] Fuller W.-E (1914). – Flood flows, *Trans. A.S.C.E. LXXVII*, p564

[9] Jarvis C-S. (1926). – Flood flow characteristics. *Trans. A.S.C.E,* **Vol 89**, p1073

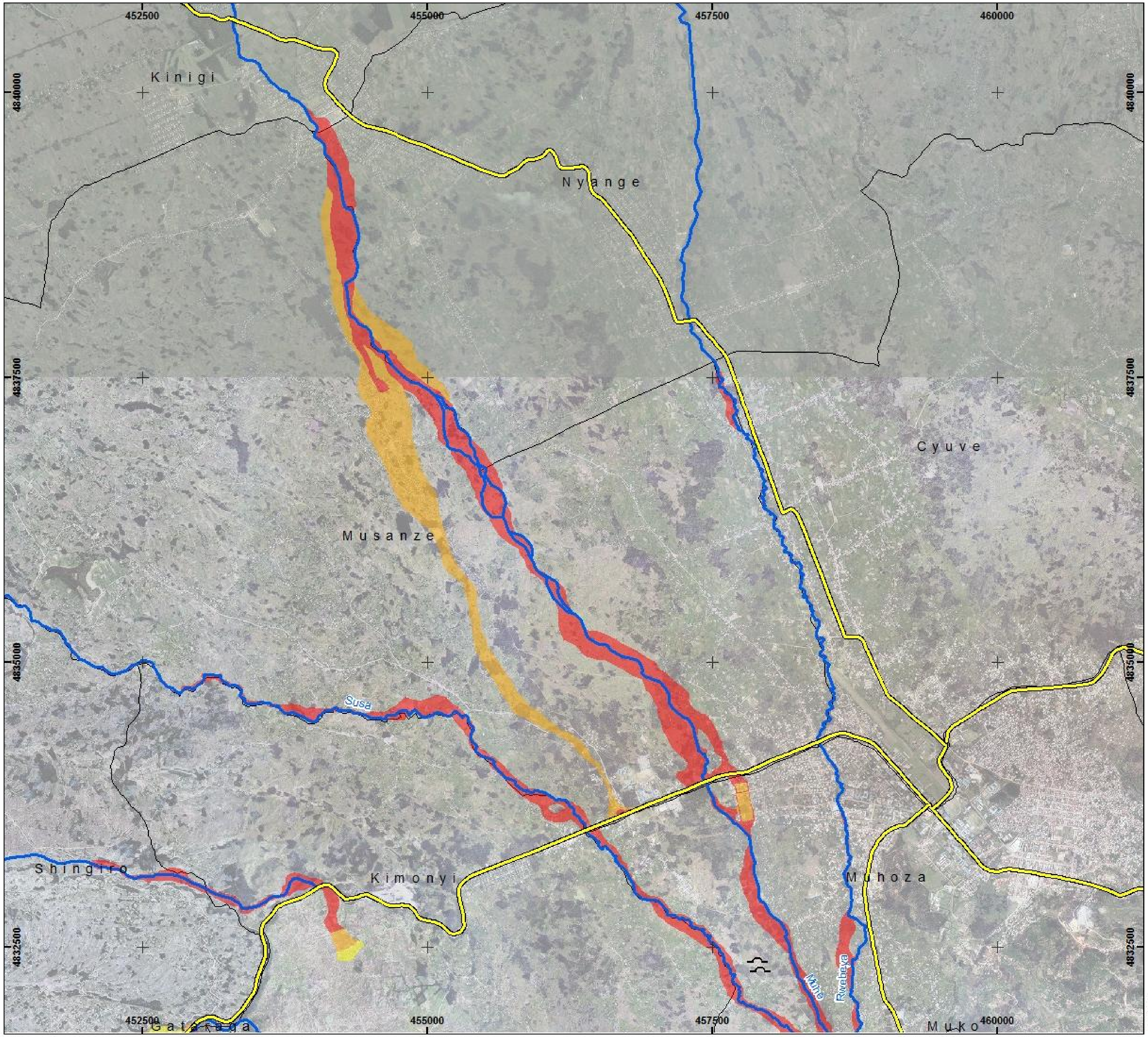
[10] Ministère de l'Agriculture, SRAE, DASH, CTGREF (1980). – *Synthèse nationale sur les crues des petits bassins versants*. Fascicule 3 : la méthode CRUPEDIX, Juillet 1980

[11] SOGREAH (1992). "Etude de faisabilité des 3 aménagements hydroélectriques de Nyabarongo, Rusumo-Rugezi et Akanyaru" pour le compte.du ministère des travaux publics, de l'énergie et de l'eau. Rapports 401490 de juin 1992.

Annex 4. Rainfall station's fits

Annex 5. Flood risk maps for 100-years flood

The maps on the following pages show the flood prone areas for a 100 years return period, which, combined with the water depth, result in the flood risk classification for people.



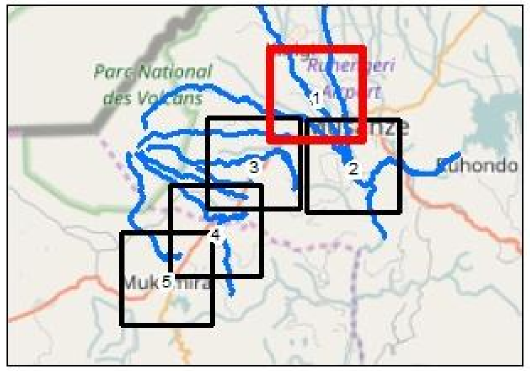
INTEGRATED WATER RESOURCES MANAGEMENT

FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Legend
Witnessed caves
National Road
River Channel
Sector
Floodplain for 100-year return period flood
Floodrisk for 100 years return period flood
Low
Moderate
High

Page 1 of 9
Susa, Muhe and Rwebeya rivers - Upstream



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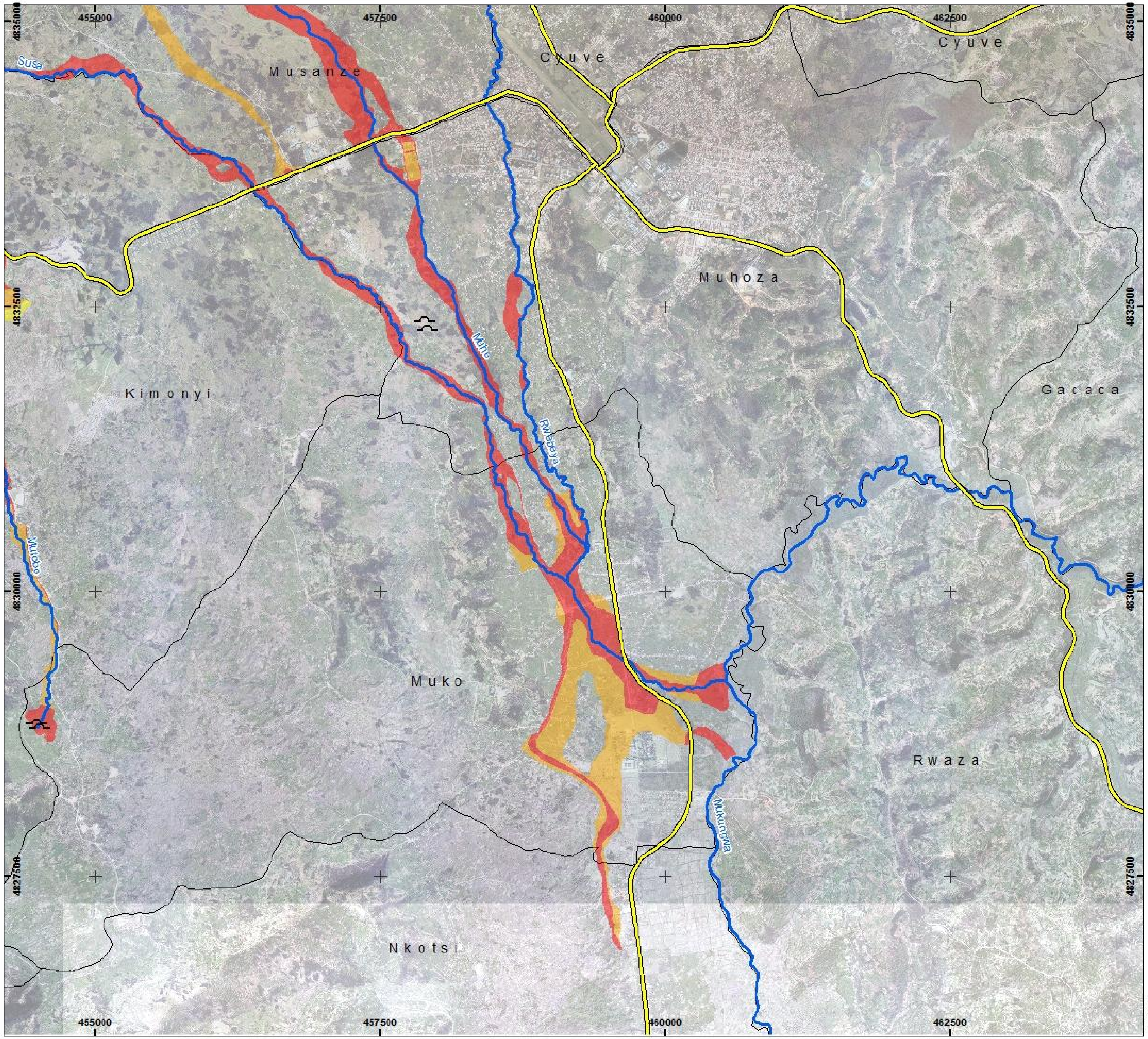

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INTEGRATED WATER RESOURCES MANAGEMENT

FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Legend

- Witnessed caves
- National Road
- River Channel
- Sector

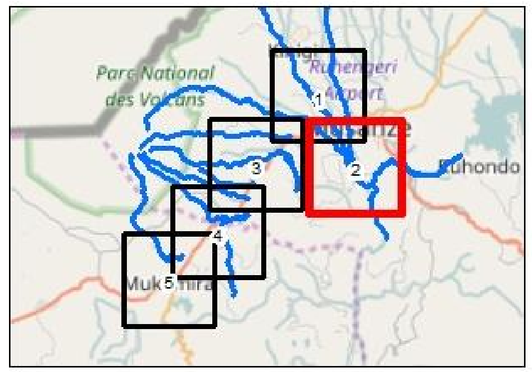
Floodplain for 100-year return period flood

Floodrisk for 100 years return period flood

- Low
- Moderate
- High

Page 2 of 9

Susa, Muhe and Rwebeya rivers - Downstream



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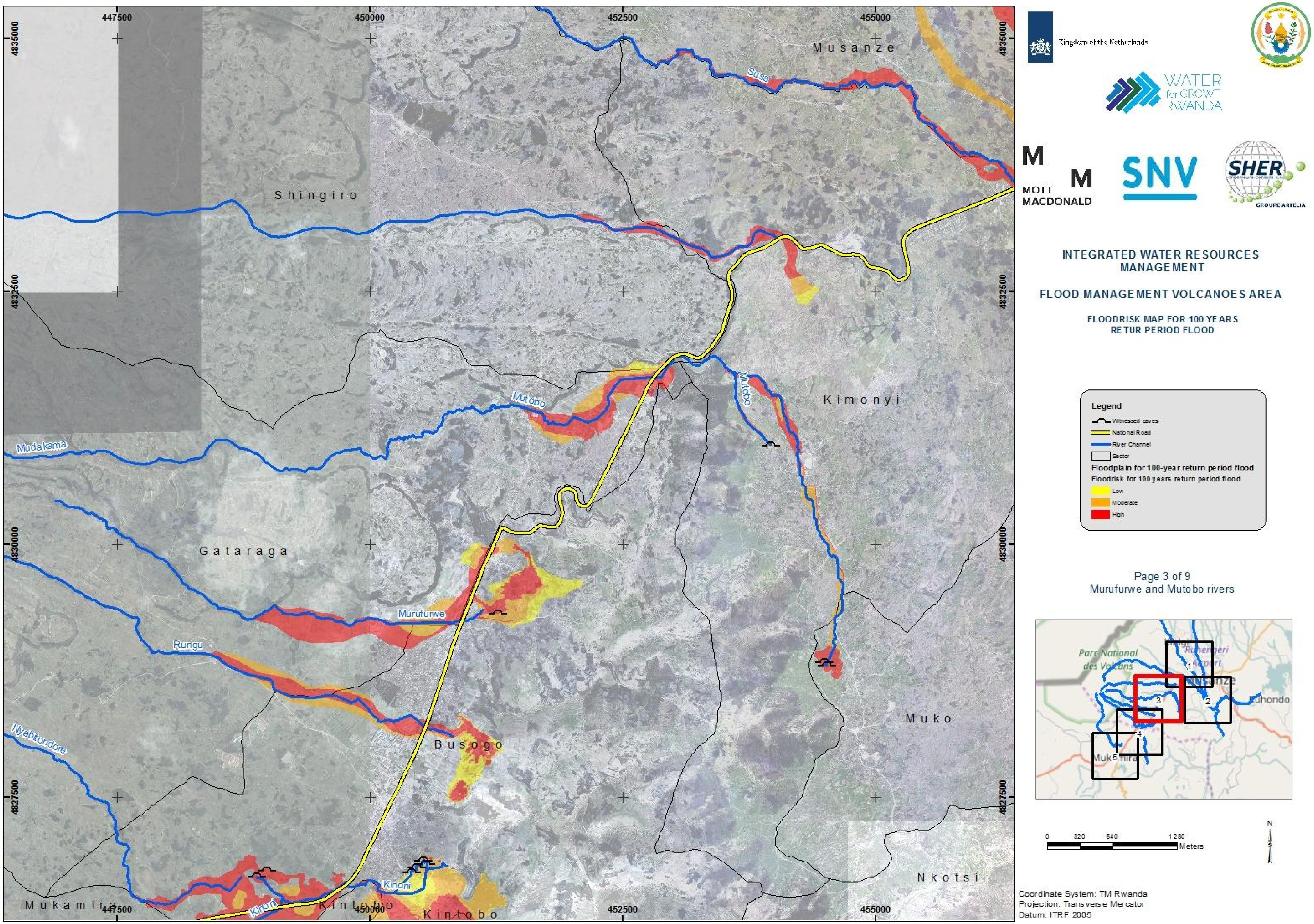
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450000
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Musanze
Shingiro
Kimonyi
Gataraga
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Muko
Nkotsi
Mukamira
Kintobo
Susa
Mutobo
Mudakama
Murufurwe
Rungu
Nyabitondore
Kinoni
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INTEGRATED WATER RESOURCES MANAGEMENT
FLOOD MANAGEMENT VOLCANOES AREA
FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD
Legend
Witnessed caves
National Road
River Channel
Sector
Floodplain for 100-year return period flood
Floodrisk for 100 years return period flood
Low
Moderate
High
Page 3 of 9
Murufurwe and Mutobo rivers
Parc National des Volcans
Ruhengeri Airport
Ruhondo
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N
Coordinate System: TM Rwanda
Projection: Transverse Mercator
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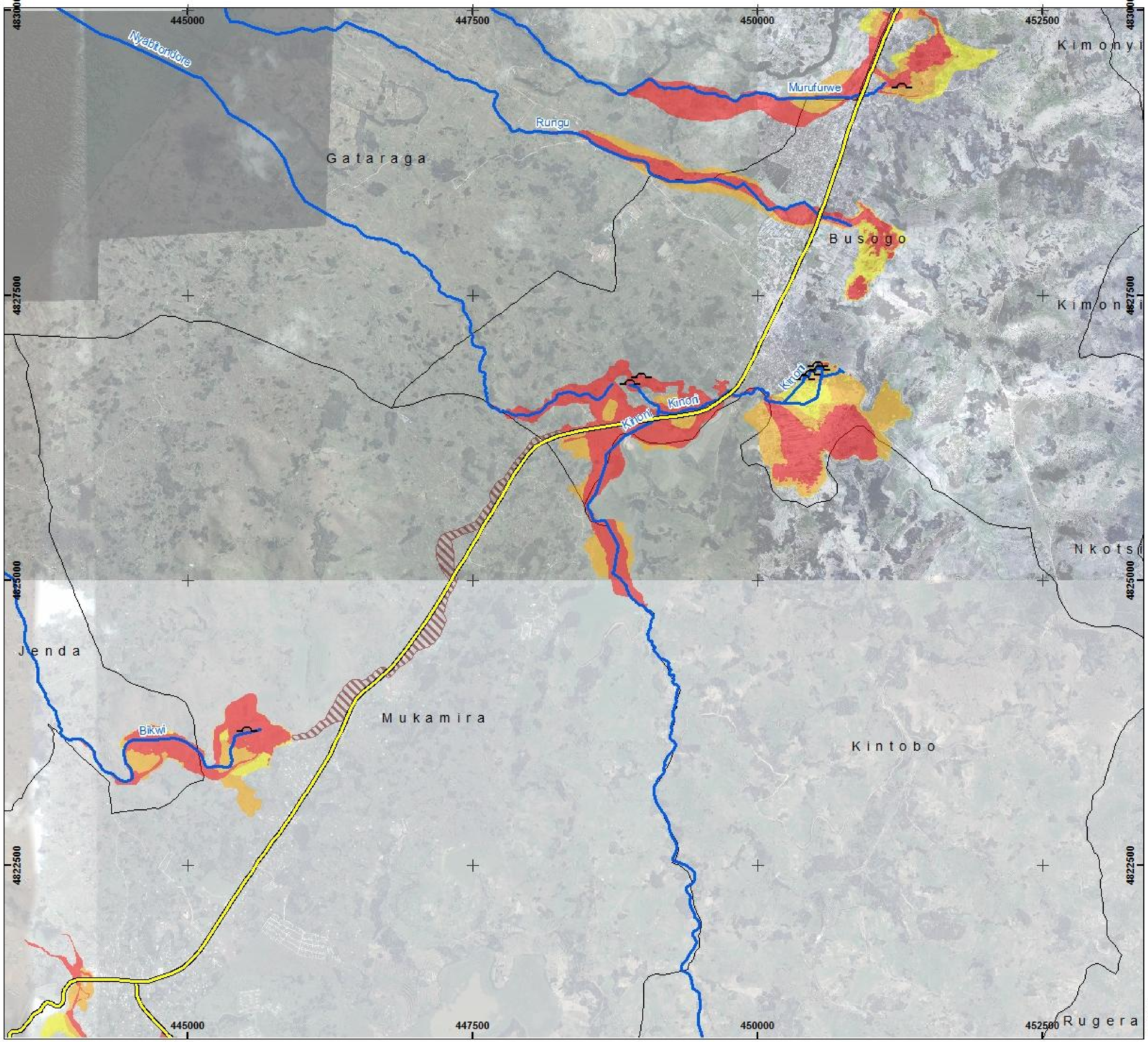


INTEGRATED WATER RESOURCES MANAGEMENT

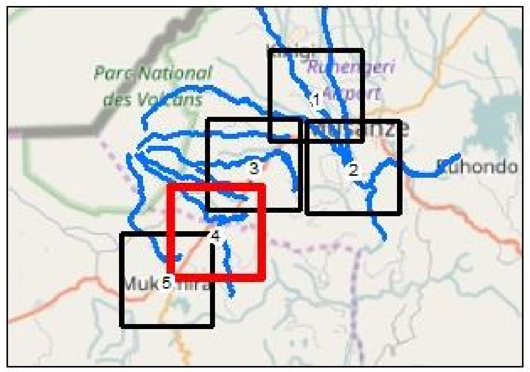
FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Legend
- Witnessed caves
- National Road
- River Channel

Floodplain for 100-year return period flood
Floodrisk for 100 years return period flood
- Low
- Moderate
- High
- Flooded area in case of Bikwi's lowland overflow
- Sector

Page 4 of 9
Rungu, Kinoni, Nyabitondore and Bikwi rivers



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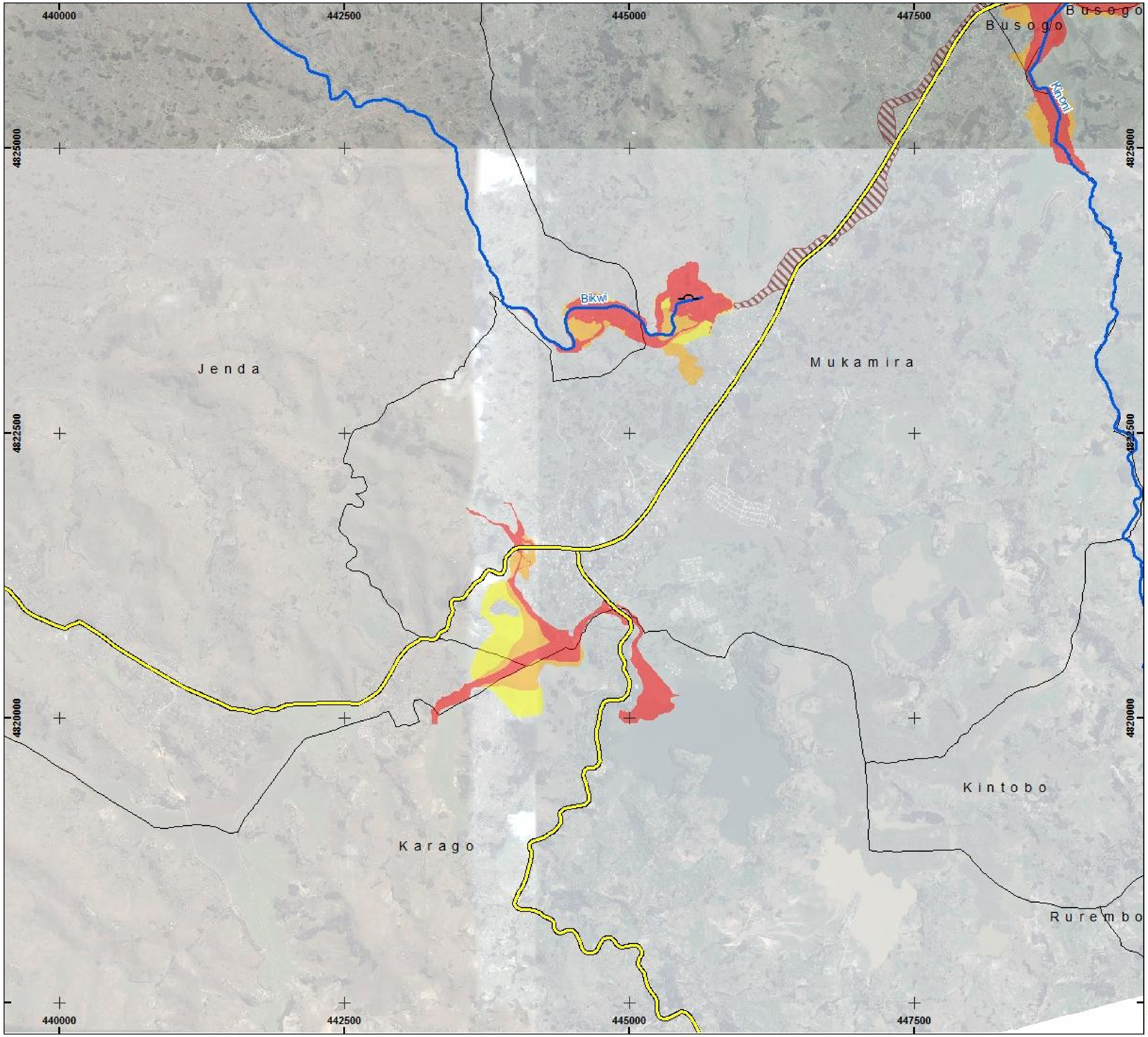
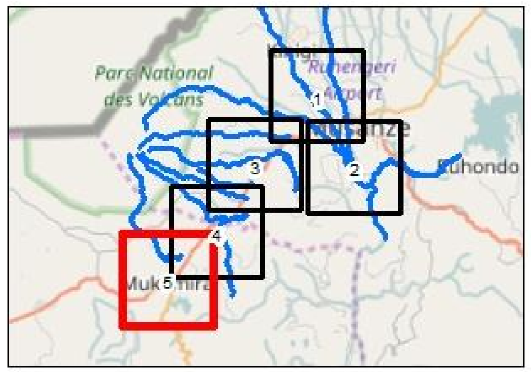


INTEGRATED WATER RESOURCES MANAGEMENT

FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Page 5 of 9
Bikwi and Mukamira rivers



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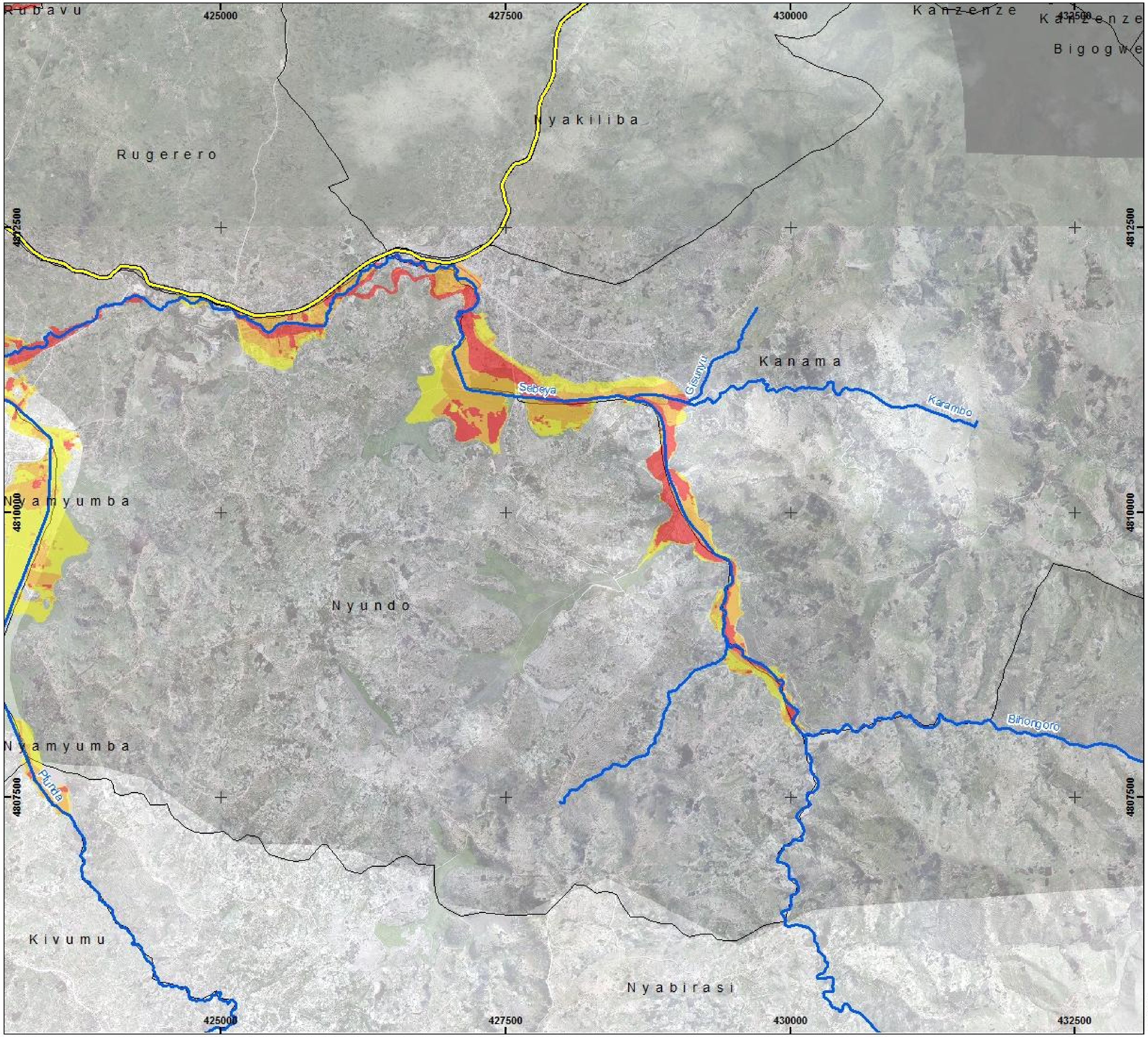


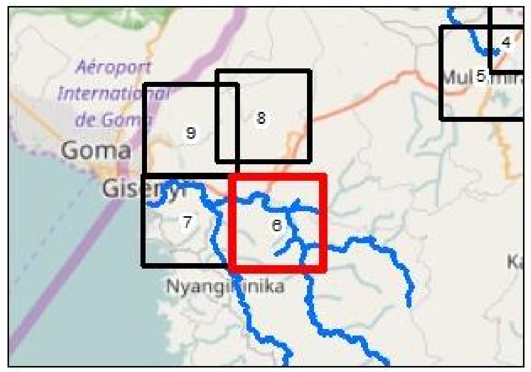
INTEGRATED WATER RESOURCES MANAGEMENT

FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Legend
Witnessed caves
National Road
River Channel
Sector
Floodplain for 100-year return period flood
Floodrisk for 100 years return period flood
Low
Moderate
High

Page 6 of 9
Upstream Sebeya river



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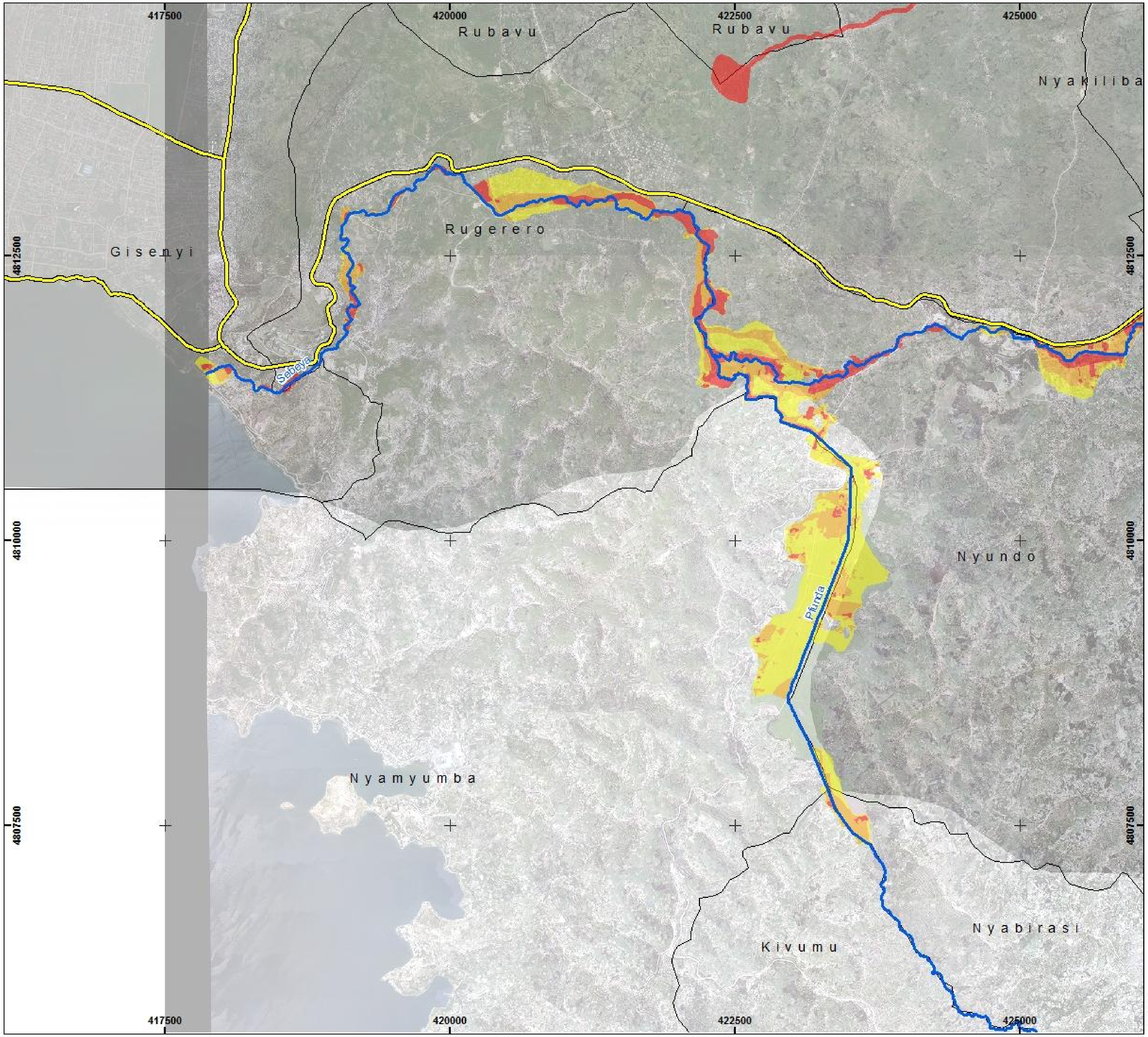

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FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Legend

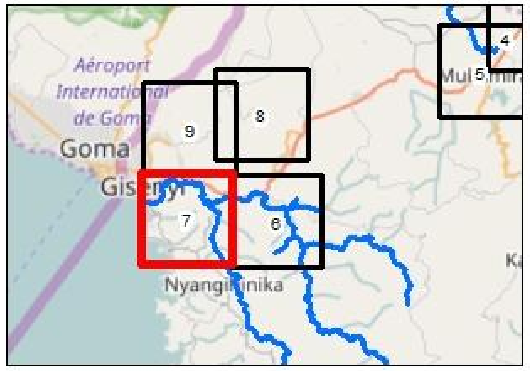
- Witnessed caves
- National Road
- River Channel
- Sector

Floodplain for 100-year return period flood

Floodrisk for 100 years return period flood

- Low
- Moderate
- High

Page 7 of 9
Downstream Sebeya and Pfunda rivers



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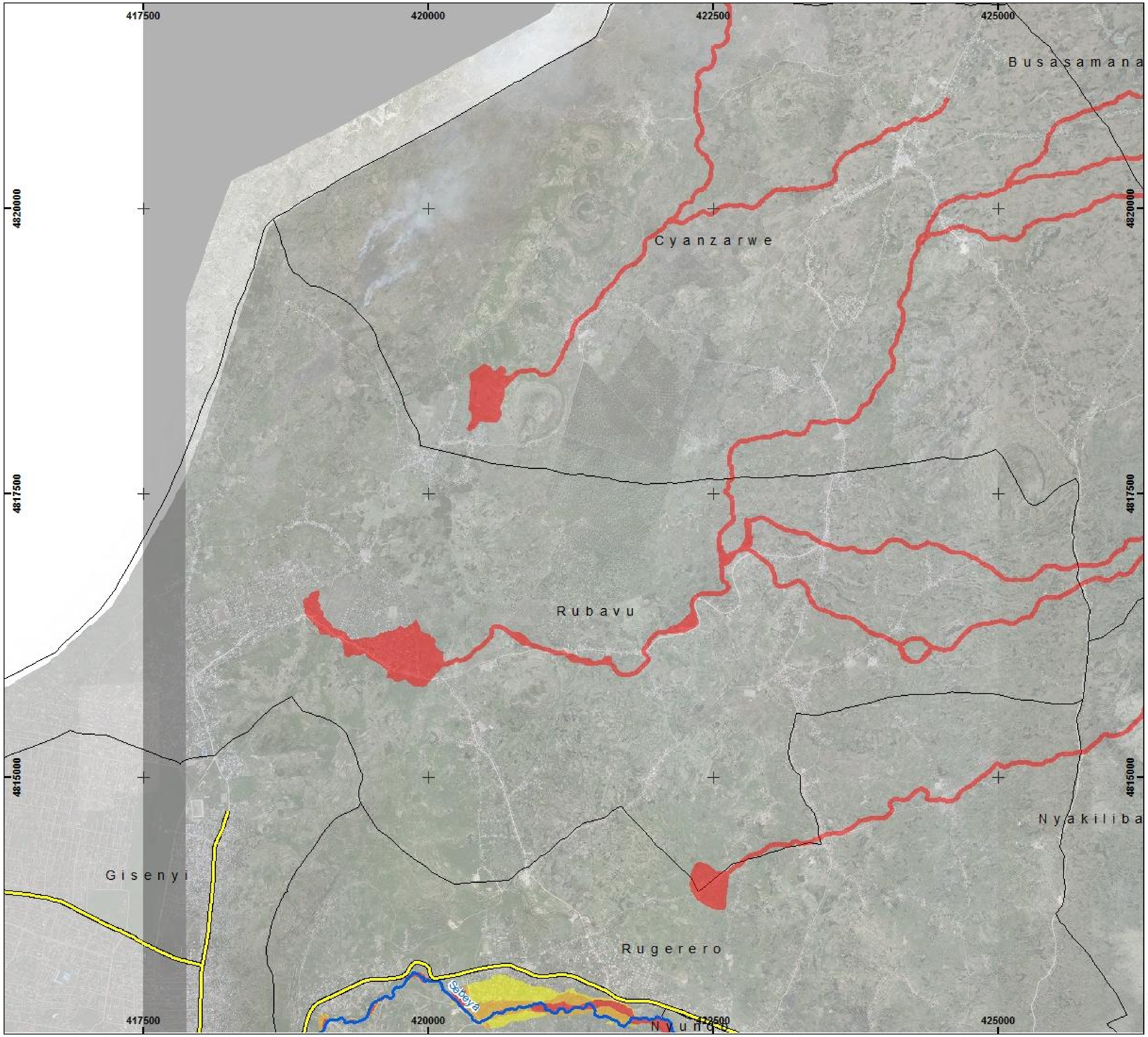

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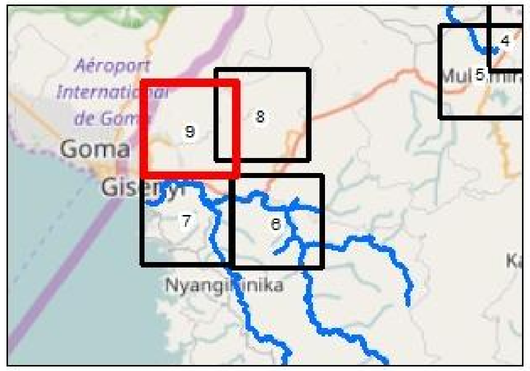
FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Legend
- Witnessed caves
- National Road
- River Channel
- Sector
- Floodplain for 100-year return period flood
- Floodrisk for 100 years return period flood
  - Low
  - Moderate
  - High

Page 8 of 9
Thalwegs North-East of Gisenyi: downstream



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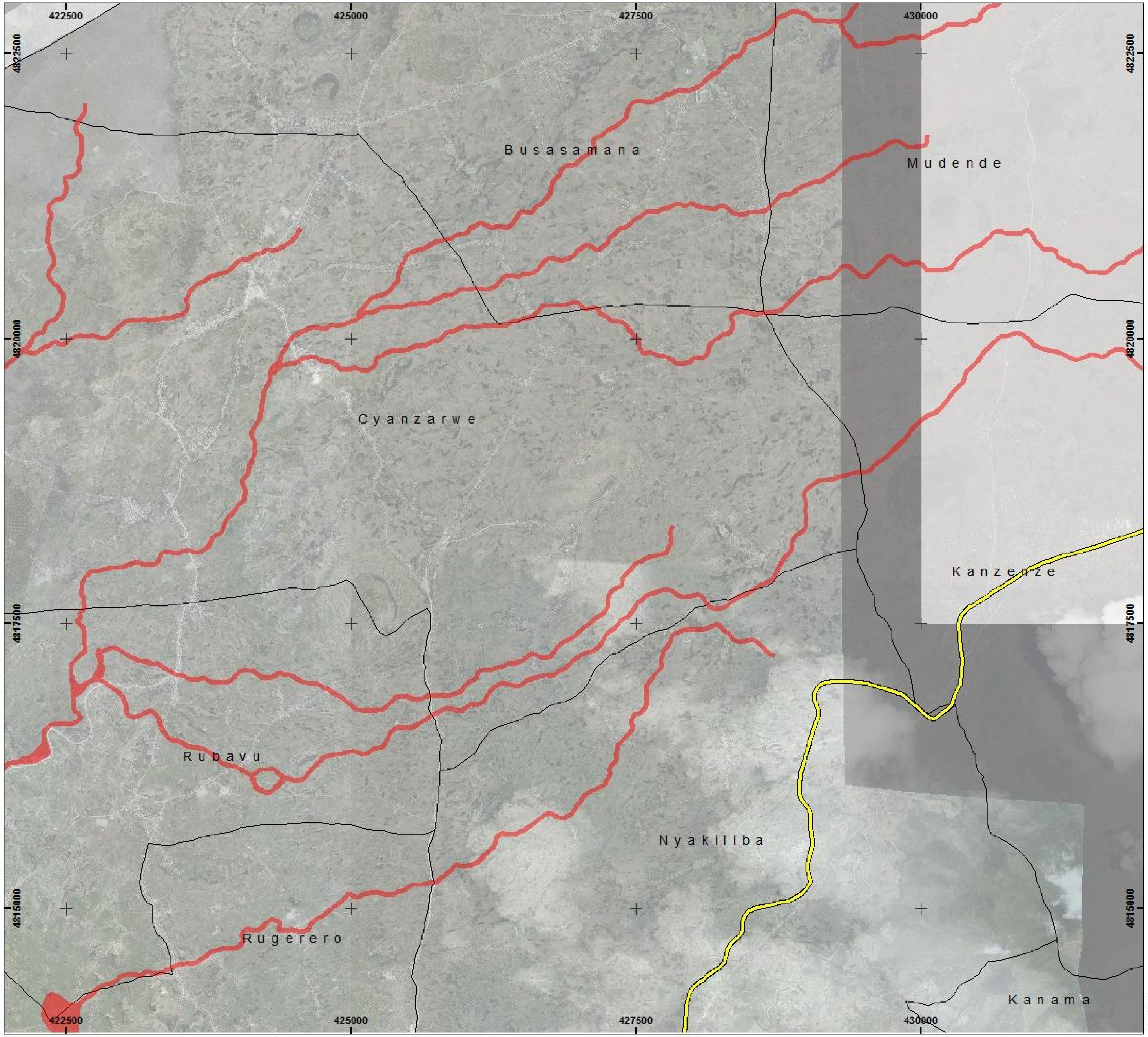

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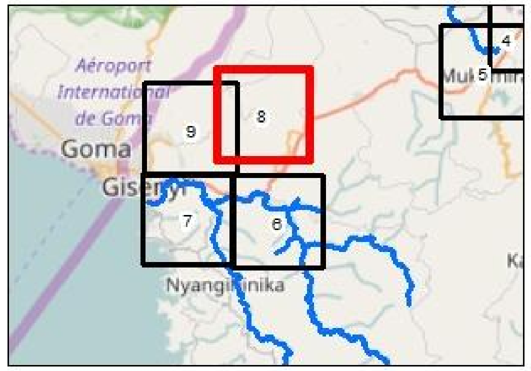
FLOOD MANAGEMENT VOLCANOES AREA

FLOODRISK MAP FOR 100 YEARS RETUR PERIOD FLOOD

Legend
Witnessed caves
National Road
River Channel
Sector
Floodplain for 100-year return period flood
Floodrisk for 100 years return period flood
Low
Moderate
High

Page 9 of 9
Thalwegs North-East of Gisenyi: upstream



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