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Evaluation of rainfall-runoff modelling data in Sebeya Catchment, Rwanda

Recommendations for improved flood hazard analysis

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Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund University

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Abstract

Rwanda has experienced an increase in the frequency of riverine floods since the mid 2000s, and the future impact of climate change on the hydrological cycle is uncertain. Flood hazard analysis is one tool used to reduce flood risks; the analysis is often based on models which requires hydrological and meteorological data. New hydrological measurement stations have been installed at select locations in Rwanda, such as Sebeya Catchment. This thesis evaluated the role of hydrological models in flood hazard analysis in Rwanda by reviewing previous hydrological studies and evaluating a HEC-HMS rainfall-runoff model of Sebeya Catchment. The hydrological telemetry data was found to not be suitable for a continuous model due to the short timeseries and the long-term daily stage data lacked rating curves. The rainfall data was only available as daily recordings, unsuitable for event-based models. To improve the performance of hydrological models in Sebeya Catchment, it is proposed that alternative data, such as satellite rainfall data, are investigated. To improve the data available in Rwanda required for hydrological modelling capacity building in database management is recommended within Meteo Rwanda and Rwanda Water Resources Board. In addition, the locations and installation process of new hydrological stations should be reviewed.

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1. Introduction

In Rwanda the most common type of flooding are riverine floods, as the country has a high number of rivers and wetlands. Riverine, or fluvial, floods are caused by high precipitation levels in the catchment or blockage of the flow. Major flood events have in the past resulted in loss of agricultural crops, environmental degradation, soil erosion, landslides, infrastructure damage, injuries, and fatalities (MIDIMAR, 2015). The frequency and impact of floods in Rwanda have increased since the mid 2000s (MIDIMAR, 2015). Climate change will change the weather patterns around the world. In some areas it will lead to increased rainfall over longer time periods with the consequence of more frequent fluvial flooding, it can also lead to more frequent and intense cloudbursts causing pluvial floods (European Comission, n.d.). Conversely, higher temperatures can lead to a reduced streamflow in catchments due to a higher evapo-transpiration (Umugwaneza, et al., 2021).

One important tool to reduce flood risk in Rwanda is flood hazard analysis which can be used to construct development plans in both urban and rural areas (MIDIMAR, 2015). Flood hazard analyses are often based on modelling and simulation of future scenarios, which in turn require a detailed understanding of the hydrological processes in the catchments. It is important to advance the understanding of these hydrological processes in flood prone areas, in particular the rainfall-runoff effects on the river flows, to improve the quality of flood hazard analysis in Rwanda. Rainfall-runoff models are used to find peak flow values and runoff volumes in catchments, these parameters can in turn be used to identify flood inundation areas and to control flood damage in areas (Namara, et al., 2020). The models require, at minimum, precipitation data and river flow data. Further on, information on infiltration, runoff, topography, drainage systems, and land cover is needed. If this information is lacking the estimation of floods becomes complicated if not impossible. When the National Risk Atlas of Rwanda was constructed, Rwanda was missing much of the hydrological and hydraulic data needed for flood hazard analysis (MIDIMAR, 2015). However, there has been recent investments in both hydrological knowledge and data collection in Rwanda and this should have improved the conditions to construct rainfall-runoff models.

Sebeya Catchment in north-western Rwanda has been having reoccurring problems with flooding from the Sebeya River, particularly around the villages Mahoko and Nyundo. A large flood with devastating consequences occurred in March 2018, which caused several deaths and a large amount of property damage (interview Section 4.2.3.3; BRL Ingénierie, 2020). Recently, there have been construction of flood mitigating measures in the catchment and several newly installed hydrological measurement stations in the catchment.

1.1. Thesis Aim

The aim of this thesis is to improve flood hazard analysis in Sebeya Catchment through the following objectives:

- evaluate how hydrological models for flood hazard analysis have been performing in Rwanda and what their constraints were
- describe current flood features and hazards in Sebeya Catchment based on previous studies, site visits and interviews
- assess the quality of the current hydrological and meteorological data in Sebeya Catchment with regards to their application in hydrological modelling
- develop a hydrological model of Sebeya Catchment using HEC-HMS
- identify recommendations for improved flood hazard analysis in Sebeya Catchment and Rwanda

1.2. Thesis Outline

Firstly, the methodology of this thesis is presented, the section outlines how the meteorological, hydrological, and geographical data were collected, how the site visit to Sebeya Catchment was conducted, how the interviews in the catchment were carried out, and how HEC-HMS was applied to model the rainfall-runoff. This is followed by background information about Rwanda and specifically Sebeya Catchment is presented, including climate, topography, and catchments. The literature review presents relevant master plans and policy documents, hydrological and climate change studies conducted in Rwanda, as well as studies with similar data challenges. Next, the results from the site visit and interviews in Sebeya Catchment are presented, followed by the results of the data evaluation and modelling.

2. Methodology

The methodology used in this thesis is presented in Figure 2-1 where the links between methods, objectives and aims are shown.

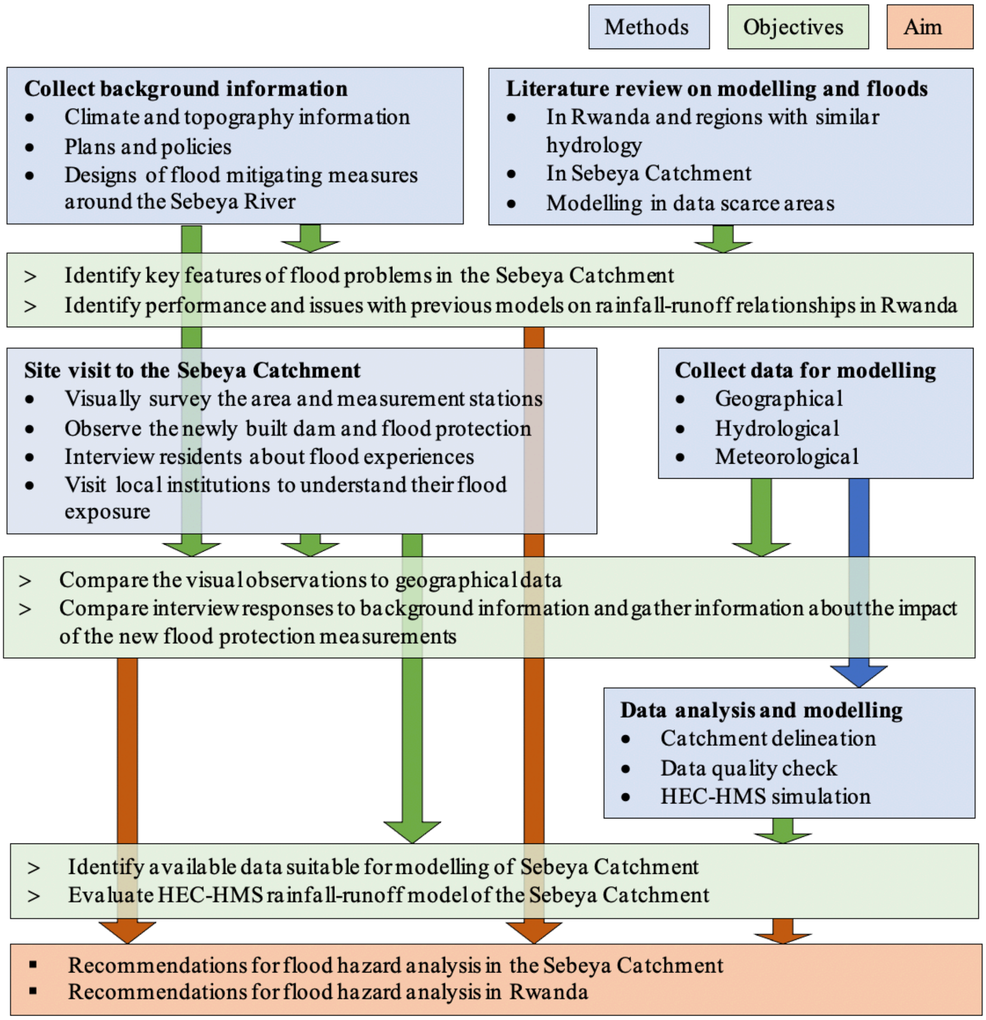


Figure 2-1 Schematic overview of the methodology.

2.1. Background on the Hydrology of Rwanda and Sebeya Catchment

Background information on Rwanda's catchments and in particular Sebeya Catchment was collected from online sources and reports obtained from Rwanda Water Resources Board (RWB).

2.2. Literature Review

Master plans, policy documents, and design documents, both published and unpublished, were obtained from RWB. Initially the literature review focused on hydrological studies conducted in Rwanda, however, the number of studies were found to be very limited and therefore the scope was expanded to include hydrological studies conducted outside of Rwanda in similar hydrological conditions or with similar data availability constraints. The review was specifically focused on studies using the HEC-HMS model.

The following search keywords were used: *Rwanda, hydrological modelling, HEC-HMS, rainfall-runoff, hilly, mountainous, missing hydrological data missing meteorological data, climate change, stage- discharge rating curve, catchment delineation*

2.3. Site Visit to Sebeya Catchment

Sebeya Catchment was visited on the 20th to 22nd of February 2022. The group consisted of a Ph.D. student at University of Rwanda (UR) and Lund University (LU) – Joseph Hahirwabasenga, two student assistants from UR and the author. The field trip was planned to take place before the start of the rainy season to have good road and accessibility conditions. The focus during the site visit was to observe the landscape, land use, the accessibility to the river and nearby areas, hydrological structures, implemented flood mitigating measurements and activities along the river, such as mining. The hydrological stations in the catchment were located, identified, and photographed using the information published by RWB.

2.3.1. Interviews

During the site visit to the Sebeya Catchment interviews were conducted to understand the residents' experiences of flooding in the area. The open-ended interview questions and sub-questions, which can be seen in Table 2-1, were translated to Kinyarwanda by the student assistants. Ten residents were interviewed by the students at three different locations near the Sebeya River. The interviewees were chosen at random but of different gender, occupation, and age. After the 6th interview it became clear that question number 2 was unclear to the interviewees and was changed. Furthermore, the supervisor of the Keya hydropower plant, the secretary at the Petit Seminaire Saint Piex de Nyundo secondary school, and a resident of the Rusongati Mountain, all located along the Sebeya River, were asked to describe their experiences of floods in the area. These interviews were also translated to English by the students.

Table 2-1 Interview questions for residents.

1	**What is the largest flood you have seen?** Ask to show on a landmark (record height and coordinates).
2	**What is an average flood?** Ask to show on a landmark. How often does it reach that level?
2 (revised)	**Was the flooding experienced on the 20th of February 2022 an average flood during the rainy season?**
3	**Have you experienced flooding of your house?** How often does it happen? What are the financial costs (highest, average)? Are you worried about your house being flooded?
4	**Have you been affected in any other way by the floods?** How often does it happen? Are you worried about your house being damaged by a landslide?
5	**How do you prepare for floods?** Are the preparations effective?
6	**Have there been any bigger projects (terracing/tree planting or mining/deforestation) conducted in your area or upstream area?** Have you noticed any change in floods since these projects have started or been completed?
7	**How do you know a flood might come?** What about warning systems? How long in advance do you know that there might be a flood?

2.4. Rainfall-Runoff Modelling Methodology

Catchment scale water resources assessments are often based on rainfall characteristics and catchment properties. Rainfall-runoff modelling studies are useful for these assessments, which have been used extensively within the field of hydrology over the past century (Munyaneza, et al., 2014). The main challenge for rainfall-runoff modelling is the lack of input data, often the spatial distribution of rainfall over a catchment area. Another difficulty is the lack of reliable flow data that is required to calibrate and validate models. In Rwanda, many catchments are ungauged or have unreliable data, thus it is particularly the quality or lack of flow data that poses a problem for modelling (Munyaneza, et al., 2014). There are several types of hydrological models available, each with their own advantages and disadvantages. For the simulation part of this thesis the HEC-HMS model was chosen as it is a model with an uncomplicated structure, requires few input data parameters, and has been used widely in previous studies (Tiwari, et al., 2018). The HEC-HMS software is free to use, readily available for download, and has an extensive learning and tutorial section. Before setting up the hydrological simulation in HEC-HMS the area of the catchment is determined using catchment delineation.

2.4.1. Catchment Delineation

Delineation is a suitable method to determine a catchment area when the topography is hilly and not greatly affected by human interference (van der Kwast, n.d.), thus it was used to determine the area of Sebeya Catchment in this report. The QGIS (version 3.22.4) software was used to delineate the catchment area and two different methods were tested:

1. Using the SAGA toolset in QGIS to delineate the catchment using a 30 meters Digital Elevation Model (DEM30) of Rwanda.
2. Using the SAGA and GRASS toolset in QGIS to delineate the catchment using a DEM30 of Rwanda and a vector file produced by RWB containing the river network in Rwanda. The river network was "burnt" into the raster at 3, 5 and 10 meters.

A detailed description of the delineation procedure is available in the Appendix. The catchment areas derived from the methods mentioned above were compared to areas representing Sebeya Catchment in other studies to identify differences.

2.4.2. The HEC-HMS Model

The HEC-HMS (Hydrological Engineering Center – Hydrological Modelling System) is a programme developed by the US Army Corps of Engineers. The models within HEC-HMS aims to relate the unknown output, in this case the catchment runoff, to known inputs such as precipitation and temperature. The HEC-HMS is designed to simulate the hydrological processes of a catchment using a set of mathematical equations. It features event infiltration, unit hydrographs and hydrological routing. As seen in Figure 2-2, the model also includes evaporation, transpiration, and soil moisture accounting which makes it possible to carry out continuous simulation. Furthermore, there are supplemental analysis tools available to forecast streamflow, depth-area reduction, erosion, and sediment transport and to assess model uncertainty. (USACE HEC, 2022a), (USACE HEC, 2022b)

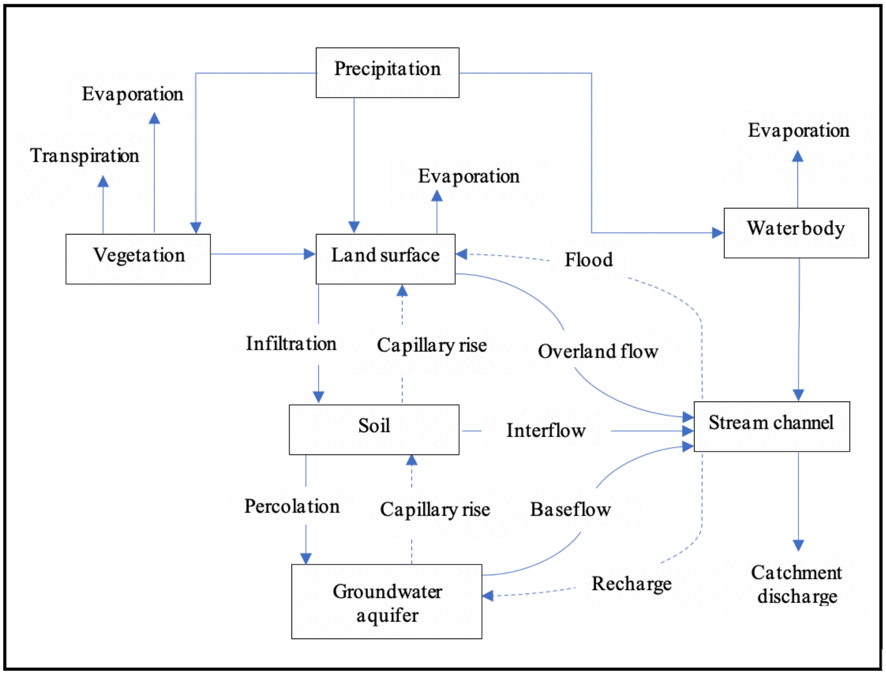


Figure 2-2 Representation of the hydrological process in a catchment in HEC-HMS. Recreated based on (USACE HEC, 2022b)

In HEC-HMS all the models are unsteady-flow models, and as differential equations are solved to describe components of the hydrological system it requires that the initial state of the system is specified (USACE HEC, 2022b). The required initial conditions depend on the specific model used but can for example be the initial state of soil moisture, the initial runoff conditions, or the initial channel flows. The boundary conditions of the models are most commonly the precipitation or upstream flow, which cause changes to the hydrological system. The models in HEC-HMS can either be event-based or continuous. The event-based models simulate a single storm which can last a few hours or up to a few days, whereas the continuous models simulate a period ranging between several days to several years. The two different model approaches differ in how infiltration, surface runoff and baseflow is treated. Event infiltration models do, for example, not consider that the soil dries through evapotranspiration and redistribution of the wetting front between storms. However, continuous models account for dry surface conditions, wet surface conditions producing runoff during and after a storm, as well as the transition between these two states. The majority of the models in HEC-HMS are event-based models. In both saturated and unsaturated conditions can the flow of water be described by Darcy's Law, see equation 1 where v is the flow per unit area, K is the hydraulic conductivity, ψ is the matric potential and z is the spatial coordinate.

Equation 1

$$v = K\frac{d\psi}{dz}$$

Another key feature is whether the models are spatially-averaged or distributed (USACE HEC, 2022b). In distributed models the spatial variations are explicitly considered whereas in spatially-averaged models the spatial variations are either ignored or averaged. Common for the spatially-averaged models are that the watershed is represented as a set of grid cells and the interaction between the neighbouring cells is dependent on the complexity of the model. Most of the models in HEC-HMS are spatially-averaged models.

In addition, HEC-HMS has both empirical and conceptual models (USACE HEC, 2022b). The empirical models are based on statistical and mathematical relationships found from observed inputs and output; these models are sensitive to the conditions during the development of the relationship. The conceptual models are based on the principles of conservation of mass, energy and momentum. All models in HEC-HMS are deterministic, as opposed to stochastic, i.e., the input is known and the process the model describes is assumed to not have any random variation (USACE HEC, 2022b). The parameters can be fitted or measured, and HEC-HMS models include both. The measured parameters models include parameters that can be measured directly or indirectly such as hydraulic conductivity. Fitted parameter models find the parameters by fitting the model to observed input and output values, for instance the Muskingum routing model (USACE HEC, 2022b).

HEC-HMS version 4.9 was used to model the runoff for Sebeya Catchment. A continuous model was chosen because the available data were better suited for this type of model. Event-based modelling was deemed unsuitable due to the available meteorological data only being daily, which is further explained in sections 2.5.3 and 4.3.3.

2.4.2.1. Basin Model

To create the basin model in HEC-HMS the DEM file was imported. The catchment polygon created in the catchment delineation process in QGIS was used in HEC-HMS in the "Terrain Reconditioning" step to create a 10 metres high boarder around the catchment and create an outlet at the downstream end, in the town of Gisenyi. This step ensured that the catchment would be the same as the one determined in QGIS. The subbasins were merged and split according to the locations of the hydrological gages and Level 3 Catchments defined by the RWB (RWB, 2020c). A full description of the procedure can be found in the Appendix. The basin model is shown in Figure 2-3. The only suitable discharge data were obtained from the Nyundo station, see the results in Section 4.3.2, thus only the sub-catchments upstream of the Nyundo station were included in the model (grey area).

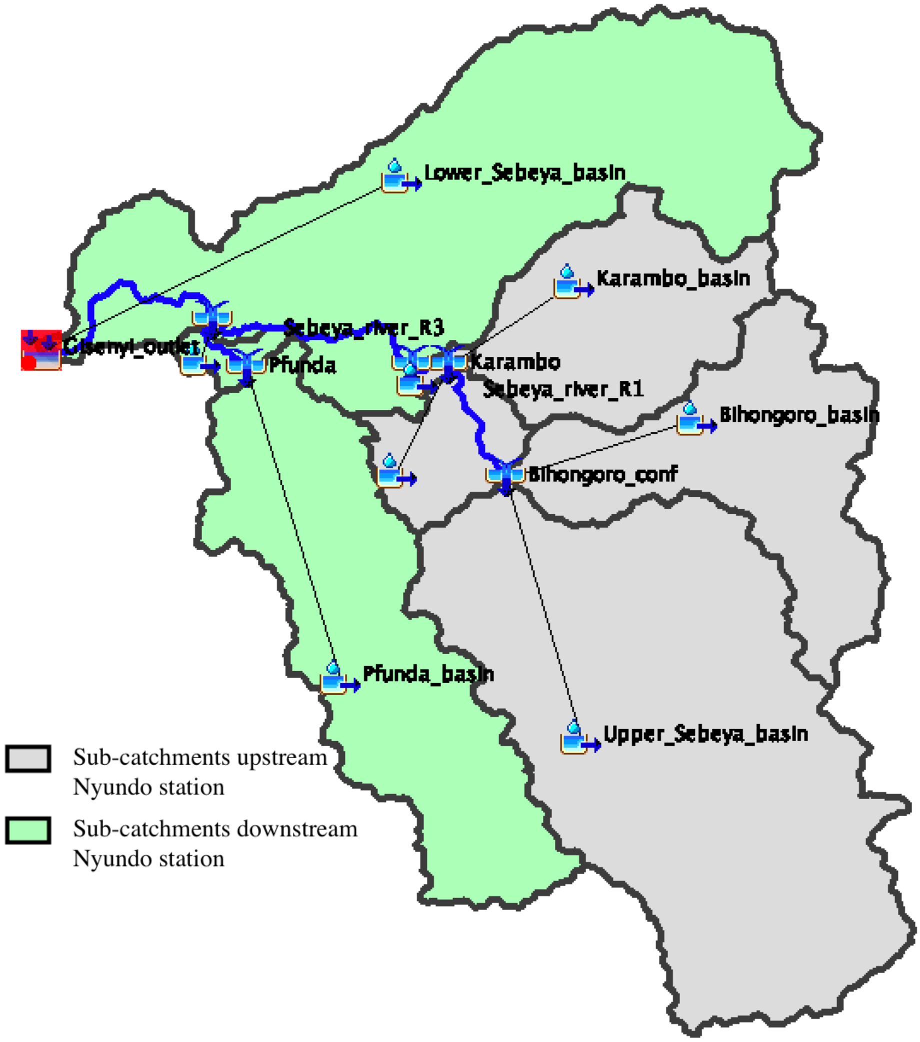


Figure 2-3 HEC-HMS basin model of Sebeya Catchment.

Table 2-2 shows the methods selected for each parameter of the basin model. These methods were selected to be suitable for continuous modelling (USACE HEC, 2023) and require a minimum amount of input data.

Table 2-2 Basin model parameters and the chosen methods

Parameter	Method
Canopy	Simple
Surface	Simple Surface
Loss	Deficit and Constant
Transform	Clark Unit Hydrograph
Baseflow	Linear
Routing	Muskingum

A Canopy method is required when using the Deficit and Constant Loss method (USACE HEC, 2023). In this model the Canopy parameters have the initial storage set to 0% and the maximum storage of 2 mm based on the land being covered by grass and deciduous trees, a crop coefficient of 1.0, and evapotranspiration occurring only during dry periods for all sub-basins (Ahbari, et al., 2018).

The Surface parameter values for the maximum storage were based on the steepness of the sub-basins and the type of land-use estimated from the DEM and observed during the site visit, summarised in Table 2-3 (Ahbari, et al., 2018).

Table 2-3 Surface parameter values.

Sub-basin	Initial storage (%)	Max storage (mm)
Upper_Sebeya_basin	0	1
Bihongora_basin	0	1
Karambo_basin	0	1
Mid_Sebeya_basin_S1	0	5
Mid_Sebeya_basin_S2	0	5

Table 2-4 shows the values used for each sub-basin for the Loss method. The imperviousness is set to the percentage of land used for settlements, 1% (Ministry of Environment, 2018). The soil is described as having a high infiltration capacity and well-drained (Ministry of Environment, 2018), and according to USDA-SCS soil classification a well-drained soil has a infiltration rate of 3.8-7.5 mm/h (Muthu & Santhi, 2015). The initial deficit and max storage are initial values based on values used in a study by Ahbari et al. (2018).

Table 2-4 Loss parameter values.

Sub-basin	Initial deficit (mm)	Max storage (mm)	Constant rate (mm/h)	Impervious (%)
Upper_Sebeya_basin	5	500	5	1
Bihongora_basin	5	500	5	1
Karambo_basin	5	500	5	1
Mid_Sebeya_basin_S1	5	500	5	1
Mid_Sebeya_basin_S2	5	500	5	1

The Transform method used in this model is the Clark Unit Hydrograph, which is a synthetic hydrograph, i.e. not developed from analysing observed hydrograph but instead developed using the time-area curve method (USACE HEC, 2023). The time to concentration (T_c) and storage coefficient (R) values were calculated for each sub-basin using the basin characteristics obtained from HEC-HMS. The parameter values are presented in Table 2-5. The Clark Unit Hydrograph is based on the continuity equation, see Equation 2 where dS/dt is the rate of change of water in storage at the time t, I_t is the average inflow to storage at time t and O_t is the outflow from storage at time t, (USACE HEC, 2022b).

Equation 2

$$\frac{dS}{dt} = I_t - O_t$$

Table 2-5 Transform parameter values.

Sub-basin	Time to concentration (h)	Storage coefficient (h)
Upper_Sebeya_basin	16	30
Bihongora_basin	11	21
Karambo_basin	9	16
Mid_Sebeya_basin_S1	8	14
Mid_Sebeya_basin_S2	3	5

The Baseflow method was chosen to be linear reservoir baseflow, in which two reservoirs were used each with a partition fraction of 0.5. One ground water step was used for each reservoir. The groundwater storage coefficient was estimated by trial and error with initial values obtained from the HEC-HMS User Manual (USACE HEC, 2023). The coefficients were chosen to be 10 and 1000 hours for reservoir one and two respectively. Muskingum was chosen as the Routing method, the parameter values were found by trial and error and resulted in Muskingum K set to 5 h, Muskingum X set to 0.1 and the number of sub-reaches set to 5 for all reaches. The Muskingum routing model uses a simple finite difference approximation of the continuity equation, see equation 3 where *I* is the inflow, *O* is the outflow rate, and *S* is the storage (USACE HEC, 2022b).

Equation 3

$$\left(\frac{I_{t-1}+I_t}{2}\right)-\left(\frac{O_{t-1}+O_t}{2}\right)=\left(\frac{S_t+S_{t-1}}{\Delta \mathrm{t}}\right)$$

2.4.2.2. Meteorological Model

The meteorological model used the Specified Hyetograph method. The GisenyiAero meteorological station was used to provide the rainfall data for the entire catchment (see Section 4.3.3 for data evaluation results).

2.4.2.3. Control Specifications

The model was set to run for the entire period of the available discharge data for the Nyundo telemetry station, August 2020 to December 2021.

2.4.2.4. Calibration and Validation

The calibration of the model consisted of modifying the parameters one by one to improve the fit of the result to the observed values. For a continuous model the focus is on the flow volume, the performance metrics, and the flow frequency. A resulting flow volume within +/- 10 % of the observed volume and a Nash-Sutcliffe Value (NSE) of the observed vs. calculated discharges above 0.5 is satisfactory. Three parameters were focused on during calibration; the Deficit and Loss which impacts the initial volume of the peak (initial loss) and the entire magnitude of the hydrograph (constant loss rate), the Clark Unit Hydrograph values which translates the hydrograph back and forth in time (time of concentration) and the peak and attenuation of the unchanged volume (storage coefficient), and the Linear Reservoir values which affect the travel time of the interflow and baseflow (GW coefficients). (USACE HEC, 2023)

No validation was done as the length of hydrological timeseries were insufficient, see the data evaluation results in section 4.3.2.

2.5. Data Collection and Evaluation for Hydrological Modelling

The following section outlines how the geographical, hydrological, and meteorological data used for modelling were obtained. Figure 2-4 shows how the different types of data were used in the analysis.

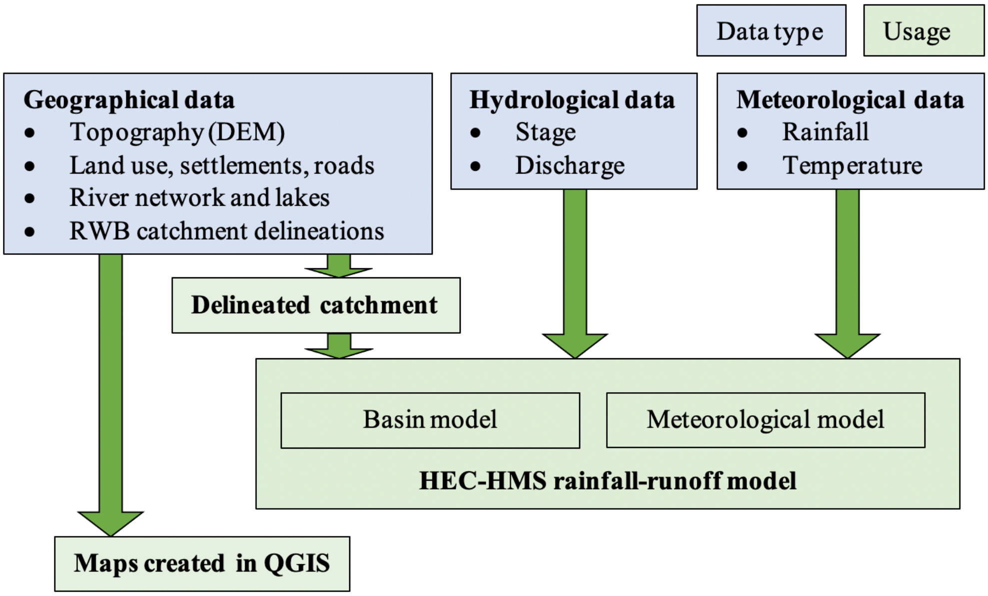


Figure 2-4 The usage of different types of data.

2.5.1. Geographical Data

Geographical data were obtained through internet searches and by sources suggested by staff from RWB and UR. The obtained data were validated against observations made during the site visit, such as river paths and land use. The following geographical data were obtained and used for analysis in this report:

- The Digital Elevation Model (DEM), Shuttle Radar Topography Mission (SRTM) file was obtained from the Regional Centre for Mapping of Resources for Development (RCMRD, 2018) in 30 metres resolution.
- Shapefiles containing Administrative Boundaries in Rwanda were obtained from Humanitarian Data Exchange/National Institute of Statistics of Rwanda (HDX, 2022)
- A shapefile containing National Parks was obtained from SDI Hub (SDI Hub/ArcGIS Hub, 2022).
- Shapefiles containing Catchment Level 1, 2 and 3 were obtained from RWB's GeoPortal (RWB, 2020a) (RWB, 2020b) (RWB, 2020c).
- Rwanda's river network shapefile was obtained from RWB's GeoPortal (RWB, 2021a).
- A shapefile containing Rwanda's lakes was obtained from RWB's GeoPortal (RWB, 2021b).
- Settlements, cities, and villages shapefiles were obtained from Open Street Map/ArcGIS Hub (ArcGIS Hub, 2020b).

2.5.2. Hydrological Data

The Rwanda Board of Water Resources (RWB) was established in 2020 and is responsible for implementing national policies, laws, and strategies relating to water, including establishing flood management strategies and forecasting water availability. The organisation is also required to collaborate with other regional and international bodies with similar missions. (RWB, 2022a) The RWB is an affiliated agency of the Ministry of Environment (MoE) (Republic of Rwanda, 2022a) and provides two online services: the "Rwanda Water Portal" (https://waterportal.rwb.rw) containing hydrological data on surface water and groundwater as well as catchment plans, legal and policy document; and the "IWRM Geo-Portal" containing geographical data (https://www.geoportal.rwb.rw). Table 2-6 lists all stations available for Sebeya Catchment in the WaterPortal, along with the type of data and start and end date of the recordings. No detailed technical information could be found about the stations or how the data were recorded.

Table 2-6 Hydrological stations within the Sebeya Catchment.

Station name	Type	Data	Start date	End date*
Gisenyi-Kivu	Daily	Stage	01-01-1974	28-02-2013
	Daily	Stage	01-03-2016	31-01-2017
Nyundo	Daily	Stage	01-01-1974	11-08-2014
		Discharge	01-01-1974	11-08-2014
Gisenyi-Sebeya	Daily	Stage	01-01-1974	11-08-2014
Nyundo	Telemetry	Stage	01-03-2018	29-11-2021
		Discharge	01-08-2020	29-11-2021
		Velocity	21-04-2017	29-11-2021
Karambo-Mahoko	Telemetry	Stage	25-01-2020	06-03-2020
Pfunda	Telemetry	Stage	25-01-2020	01-05-2022
Sebeya-Mahoko	Telemetry	Stage	23-06-2020	01-05-2022
Karambo	Telemetry	Stage	29-07-2020	02-11-2020
Bihongora	Telemetry	Stage	30-07-2020	15-04-2022

**Last day of access was 1st of May 2022.*

The telemetry measurement stations started recording data at the start of 2018. The “daily data” contained daily recordings and the “telemetry data” had been recorded every 10 or 15 minutes. The percentage of missing values between the start and the end of the recordings were estimated.

Several of the stations were missing the stage-discharge control measurements required to construct rating curves, i.e. there were no or very few discharge measurements with the corresponding stages (see Table 2-7). The stations with long historical timeseries (Nyundo and Gisenyi-Sebeya) did not have continuous control measurements but they tended to be grouped over a couple of years with several years in between. The telemetry station at Nyundo recorded discharge and velocity as well as stage, as seen in Table 2-6, although the discharge observations were only available for a short period, 16 months. Moreover, there was no technical information available about how the discharge was measured and if it considered a change in the river profile due to sediment deposits or erosion. The data sets from the stations that contained both stage and discharge measurements, Nyundo daily and Nyundo telemetry, were analysed by using bivariate scatter plots and calculating the correlation coefficient. The data sets were assessed based upon the duration of the recordings, the ratio of missing data, the availability of a rating curve, and the reliability of the discharge data recordings.

Table 2-7 Discharge-stage observations for hydrological stations in Sebeya Catchment.

Station name	Discharge-stage measurements	No. of observations	Start date	End date
Gisenyi-Kivu	No	-		
Nyundo	Yes	106	31-10-1972	25-09-2020
Gisenyi-Sebeya	Yes	23	07-05-1950	23-08-2014
Karambo-Mahoko	No	-		
Pfunda	Yes	5	25-08-2020	10-11-2021
Sebeya-Mahoko	Yes	1	10-11-2021	10-11-2021
Karambo	Yes	2	25-08-2020	28-08-2020
Bihongora	Yes	5	25-08-2020	09-11-2021

2.5.3. Meteorological Data

The Rwanda Meteorological Agency (Meteo Rwanda) is also an affiliated agency of the MoE (Republic of Rwanda, 2022a) - its predecessor was established in 1963 and in 2014 the agency was moved from the Ministry of Infrastructure (MININFRA) to the MoE. The first rainfall and temperature observations were made in the 1930s (Meteo Rwanda, 2022a). Meteo Rwanda’s mission is to provide “accurate, timely weather and climate information and products for the general welfare of the peoples of Rwanda” (Meteo Rwanda, 2022b) The agency has a mandate to, among other; establish meteorological stations, collect and analyse meteorological data, and to provide meteorological information to any interested person (Meteo Rwanda, 2022b). Its historical data is accessible free of charge upon a justifiable utilisation of the data (Meteo Rwanda, 2022c). The meteorological data were requested from the Meteo Rwanda through contacts at UR and Meteo Rwanda’s web portal.

It was it not possible to obtain a full list of the meteorological stations in Rwanda despite repeated requests to Meteo Rwanda. This resulted in a lack of overview of which stations that would be suitable for hydrological modelling Sebeya Catchment, and meteorological data could only be requested by station name. From the research community in Rwanda incomplete and unofficial lists of meteorological stations in north-western Rwanda, including names and coordinates, were obtained. By mapping the stations using QGIS, the ones located in and around Sebeya Catchment could be identified and data requested from Meteo Rwanda. Data were received for nine stations, see Table 2-8, all timeseries only contained daily measurements. It was not possible to obtain detailed technical information about the stations, measurement technique or if any processing had been done to the timeseries.

Table 2-8 Meteorological stations within and surrounding the Sebeya Catchment.

Station name	Type	Data	Start date	End date*
GisenyiAero	(unknown)	Rainfall	01-01-1981	31-12-2021
		Temp. (min)	01-01-1983	31-12-2021
		Temp. (max)	01-01-1983	31-12-2021
		Relative humidity	01-03-2002	31-08-2021
Nyundo	(unknown)	Rainfall	01-01-1981	31-12-2021
Kabaya	MRG	Rainfall	01-04-2010	28-02-2022
Busasamana	(unknown)	Rainfall	20-04-2010	28-02-2022
Kanama	(unknown)	Rainfall	01-05-2011	28-02-2022
Sebeya	AWS	Rainfall	29-01-2014	11-11-2021
Rugerero	ARG	Rainfall	10-03-2018	01-05-2022
Kibisabo	AWS	Rainfall	30-01-2019	16-06-2021
Muhungwe	AWS	Rainfall	28-08-2019	12-06-2021

**Last day of access was 1st of May 2022.*

All recordings are daily. MRG (Manual Rain Gauge), AWS (Automatic Weather Station), ARG (Automatic Rain Gauge).

The rainfall timeseries were plotted and assessed for outliers, which resulted in the exclusion of the first thirteen recordings of the Sebeya station as they were extremely large (daily average: 1034mm, daily maximum 3219mm). The percentage of missing data was identified for each timeseries. Thereafter, datasets were selected for rainfall-runoff modelling based on the correspondence to periods of the selected hydrological datasets. The monthly averages for each station were plotted to assess if the distance from the lake and difference in topography had any impact on the rainfall.

3. Hydrology of Rwanda and Sebeya Catchment

Assessing water resources on catchment scale is key to understanding the water available for sustainable water resources management, particularly for agricultural purposes. Between 2009 and 2014, Rwanda moved from a centralised to a decentralised system of water resources management (Munyaneza, et al., 2014). The aim was to manage water resources in an integrated manner at catchment level instead of at administrative level. Thus, detailed understanding of the catchments became vital for sound decision making. Rwanda has a hilly landscape with altitudes ranging from 900 to 4507 meters above sea level. The highest points are in the northern area where volcanic mountains are situated. The middle part consists of undulating hills whereas the eastern part is relatively flat. The Congo-Nile Ridge extends from north to south through the western part of Rwanda. This range of mountains divides two of the largest watersheds in Africa – the Nile Basin and the Congo Basin (MIDIMAR, 2015). The Rwanda National Water Resources Master Plan (MINIRENA-RNRA, 2015), further divides the two basins into nine Level 1 catchments; Lake Kivu, Rusizi, Upper Nyaborongo, Mukungwa, Lower Nyabarongo, Akanyaru, Upper Akagera, Lower Akagera and Muvumba, as shown in Figure 3-1. The Level 1 catchments are further divided into Level 2 and Level 3 catchments.

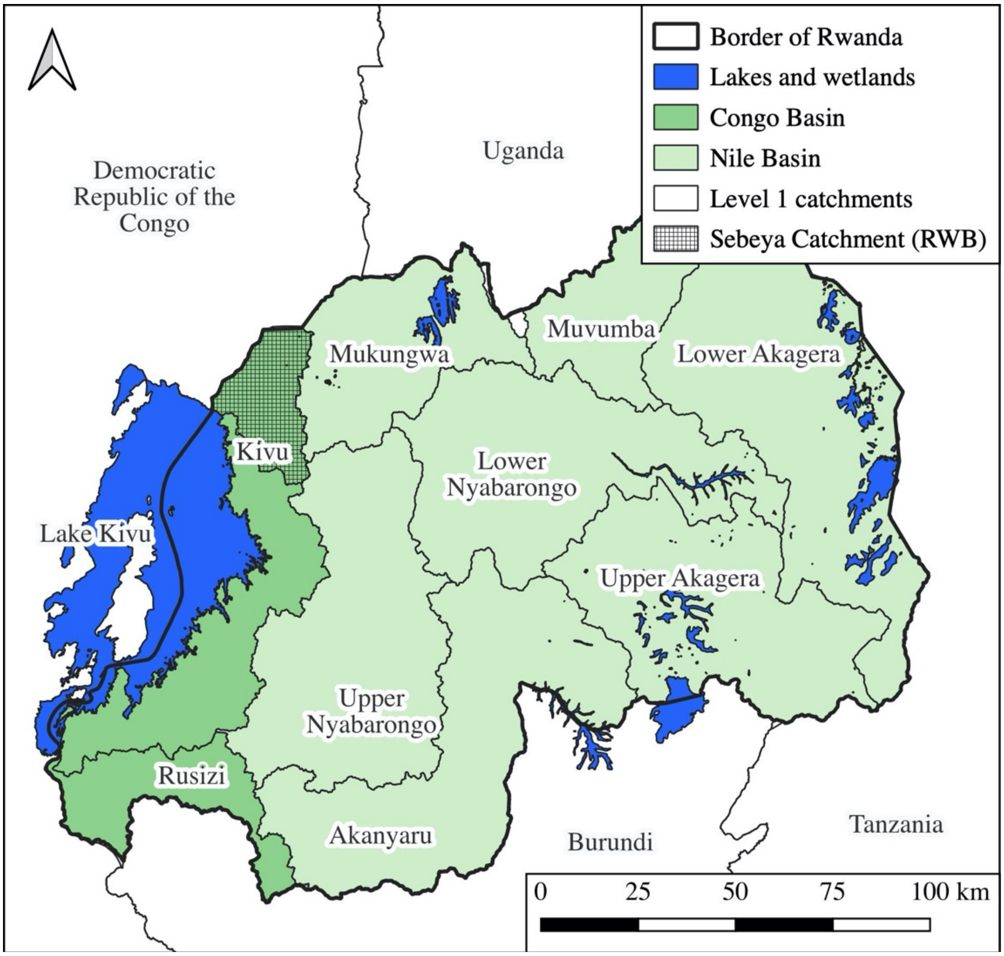


Figure 3-1 Basins, Level 1 catchments and Sebeya Catchment.

Sebeya Catchment is a Level 2 catchment located in the northern section of the Level 1 Kivu Catchment. According to the Sebeya Catchment Management Plan (2018-2024) (Ministry of Environment, 2018) the area of the catchment is 336 km^2, which equates to 1.4% of Rwanda's total surface area. The Sebeya River is 48 km long, starting in the mountainous areas then flowing in a north-westerly direction ending at Lake Kivu. The elevation in the catchment varies from 1460 m.a.s.l. in the western part by Lake Kivu to 2950 m.a.s.l. in the eastern part, see Figure 3-2. For the difference in catchment boarders (RWB vs DEM30), see Section 4.4.1.

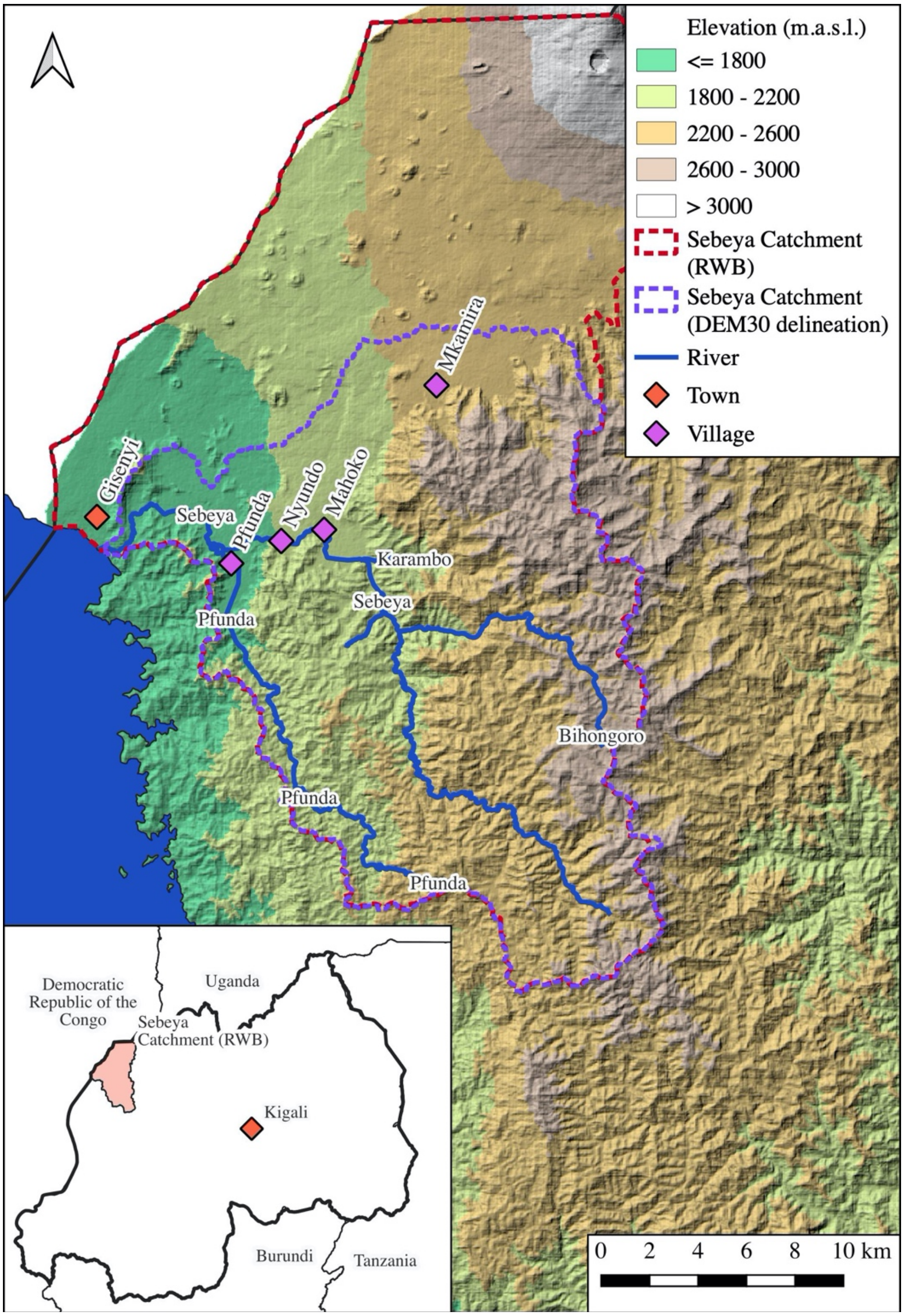


Figure 3-2 Sebeya Catchment overview and topology.

The soil in the catchment is described as primarily deeply weathered, well drained, erodible, and fertile, the surface layer consists of a dark soil originating from volcanic materials with high infiltration capacity. (Ministry of Environment, 2018) The risk of erosion is high to extremely high in most of the catchment, only excluding some areas near Lake Kivu. High sediment loads in the rivers is stated as the main source of pollution, it is caused by soil erosion from hillside agriculture as well as mining. Most of the catchment has a granite base aquifer which has a low storage capacity. However, in the norther part of the catchment the base layer consists of a highly permeable basalt layer. Due to the basalt layer's high infiltration, storage, and transmission capacity, there is an absence of perennial surface watercourses. Instead, there is a large network of underground water channels and 'dry rivers' at the bottom of valleys which carries the water during heavy rainfall to endorheic basins. The knowledge of this network of channels and basins is very limited. (Ministry of Environment, 2018)

Due to the high altitude the climate in Rwanda is considered tropical temperate. The average annual temperature is 18.5 °C and the average annual rainfall is 1250 mm (MIDIMAR, 2015). Eastern Rwanda has a drier climate whereas the western part has a wetter climate (Ministry of Environment, 2018). The rainfall is considered bimodal, i.e. two rainy seasons (Siebert, et al., 2019). According to the Sebeya Catchment Management Plan (Ministry of Environment, 2018), infiltration significantly reduces runoff in the catchment during the short rainy season (September to December), and surface flows are within the range of 1 to 2.5 m^3/s. During the long rainy season (February to May) the surface flows increase as the groundwater reserves are filled up and flash floods can occur after intense rainfall. When the Sebeya Catchment Management Plan was produced, floods were considered a problem especially in the downstream area of the catchment. A land use and land cover map was produced for the Sebeya Catchment Management Plan using radar and optical imagery from 2016-2018 it was showed that 51% of the land was covered by forest, although, half of it was considered degraded forest, including the forest in Gishwati National Park in the southern part of the catchment, 48% of the land is used for agricultural related activities, and about 1% for settlements (Ministry of Environment, 2018).

4. Results

4.1. Literature Review

No published hydrological research studies conducted in the Sebeya Catchment could be found and only a very limited number of studies regarding hydrological or climate change effect on the hydrology in Rwanda were obtained. Research has primarily been carried out in the Nyabugogo Catchment close to Kigali and the Migina Catchment in southern Rwanda. However, as the Sebeya Catchment is in a region often affected by flooding as well as having some available hydrological data, catchment plans, planning policies, and flood studies have been commissioned by governmental bodies.

4.1.1. Master Plans and Policy Documents

4.1.1.1. National Risk Atlas of Rwanda

In 2012, the Government of Rwanda requested that the Ministry of Disaster Management and Refugee Affairs (MIDIMAR) should assess the hazards and risks in the country and to develop a disaster risk profile. With support from United Nations Development Programme, the African Caribbean and Pacific European Union (ACP-EU) Natural Disaster Risk Programme, the World Bank, and the Global Facility for Disaster Reduction and Recovery (GFDRR), MIDIMAR launched the project "Development of comprehensive risk profiles for enhancing disaster management in Rwanda". The project resulted in the report "National Risk Atlas of Rwanda" but faced challenges due to the initial lack of expertise in fields such as hydrology and geology as well as a lack of a data collection system and proxy data (MIDIMAR, 2015).

Flood hazard mapping was part of the National Risk Atlas of Rwanda project (MIDIMAR, 2015). Due to lack of hydrological and hydraulic data the study used the GIS Flood Tool (GFT) developed by US Geological Survey (USGS), which produces flood hazard maps when the discharge value and stage are specified at a location. The stage was found using the Manning equation. As there were no available estimations of the coefficient of roughness, the study used the default "Manning's n". The study defined a flood as an overland water depth of 0.2 metres or above and used a return period of 25 years. Only five catchments (Sebeya, Mukungwa, Nyabugogo, Kagitumba and Nyabisindu) were mapped due to the limited data. Two detailed field surveys were conducted in the Sebeya and Nyabugogo catchment to validate the accuracy of the method. One conclusion of the study was that the GFT tool does not give information on flood parameters such as duration and speed. To improve the modelling capabilities, it was recommended that monitoring systems (i.e. hydrometric stations) should be installed at relevant locations. Furthermore, detailed assessments on local level were recommended to assist policy makers, planners, and decision makers to construct and implement flood management systems. Finally, the report strongly recommended obtaining high temporal rainfall and river discharge datasets. The final vulnerability assessment compiled in the National Risk Atlas of Rwanda did not include flood risk, primarily due to the lack of data. Instead, only drought, landslide, earthquake, and windstorms were considered.

4.1.1.2. *Rwanda National Water Resources Master Plan*

The Master Plan (MINIRENA-RNRA, 2015) was developed by MINIRENA-RNRA (formerly Ministry of Natural Resources of Rwanda (MINIRENA) and Rwanda Natural Resources Authority (RNRA) – currently Ministry of Environment) with the objective of ensuring sustainable water resources development, utilisation, and management in Rwanda. The document revised Rwanda's catchment division to the two river basins and nine Level 1 catchments presented in Section 3. The Master Plan gives an overview of the Level 1 catchments and their characteristics, such as annual rainfall and evaporation; however, it is unclear upon which sources their data is based other than "Rwandan data only". The Master Plan mentions a Water Management Information System (Water MIS) (https://watsanmis.mininfra.gov.rw) which primarily should be used to monitor water resources. This is a locked web portal hosted by Ministry of Infrastructure (MININFRA) primarily supplying information required for water providers and water permit applications. According to the Master Plan, both meteorological and hydrometric data should be provided for hydrological studies and the data should be centralised in a unique database to avoid redundancy and facilitate accessibility. The Water MIS tool is currently only providing information for Level 1 catchment monitoring of water resources and water use, and the Master Plan strongly recommends the capacity to be extended to level 3 catchments. The Master Plan emphasises that the lack of data, data quality and technical knowledge relating to data management are risk factors for the Water MIS. The Master Plan thoroughly assesses the water resources of Rwanda, however it was published in 2015 and as Rwanda is a rapidly developing country, parts of the report, such as existing measuring stations and authorities' organisation, is out of date. The Master Plan states in its introduction that separate master plans were developed for all nine Level 1 catchments. However, these reports are not available online. The catchment plans which are available on RWB's website for the Level 2 catchments are shown in the Appendix.

4.1.1.3. Water for Growth Rwanda

The Water for Growth Rwanda Programme was a joint initiative between the Netherlands and Rwanda with the aim to improve the water resources management in Rwanda and part of the IWRM programme in Rwanda. The project led to several unpublished technical reports by Euroconsult Mott MacDonald (consultant) in association with SNV (development consultant) and SHER Groupe Artelia (consultant). The documents primarily concern the design of various flood mitigating structures within the Sebeya Catchment as well as a feasibility study. The following, unpublished, design reports were obtained from the RWB:

- Sebeya Lateral Retention Dike (2020)
- Gisunyu-Karambo Protection Wall (2020)
- Bukeri Diversion Channels (2020)
- Sebeya Retention Dam (2020)

The reports present the results of geotechnical investigations at the specific sites and refers to HEC-RAS and HEC-HMS models and topographic surveys were carried out between the Bihongora confluence and Nyundo, however, the methodologies and data sources of these studies are not presented in the reports. (Water for Growth Rwanda, 2020a)

4.1.1.4. Sebeya Catchment Management Plan

The Sebeya Catchment Management Plan (2018-2024) (Ministry of Environment, 2018) was developed through the Water for Growth Rwanda Programme which was supported by the Netherlands (Mott Macdonald, n.d.). The Catchment Plan has a short introduction and methodology section, but without detailed information as to how data was collected, or which entities were responsible for which sections of the Plan. It has been aligned to relevant policy documents from the Government of Rwanda such as the Green Growth and Climate Resilience Strategy (2011) and the 7-year Government Programme: National Strategy for Transformation 2017-2024. It bases its catchment characteristics information on data from the National Water Resources Master Plan (MINIRENA-RNRA, 2015), the National Institute of Statistics of Rwanda (NISR) and studies carried out by Water for Growth Rwanda. Three specific objectives are set out for Sebeya Catchment in the Catchment Plan, the first of which is most relevant to this report:

"Implement the landscape restoration measures in priority sub-catchments which are Karambo with Sebeya downstream and Sebeya upstream, minimize floods and landslides"

The Catchment Plan ranks flooding as issue 8 out of 8 in Sebeya Catchment, after: mining exploitation, soil erosion, deforestation, soil overexploitation, insufficient rainwater harvesting for households, insufficient cattle drenching places and inaccessibility of water. Overall, the Catchment Plan is comprehensive and describes various aspects of the Sebeya Catchment management, including water resources, detailing how the IWRM practice should be implemented, as well as suggesting how to build upon the report in the future. Sources are clearly stated, including the year data was obtained, unfortunately, not all sources are found in the reference list. The hydrological section has several references and footnotes missing and some methods are not sufficiently explained. The methodology and extent of the authors' own studies are not detailed. However, there is a reference list of internal Water for Growth Rwanda reports that have been used, they are all very recent but not available online.

4.1.1.5. Flood Mapping Report

This unpublished document was commissioned by the World Bank and Global Facility for Disaster Reduction and Recovery (GFDRR) and produced by the consultants BRL Ingénierie as part of the "Development of a National Early Warning Platform for Rwanda and a Flood Early Warning System for the Sebeya River Basin" (BRL Ingénierie, 2020). The report was obtained through contacts at UR and RWB and written between 2019 to 2020. The report assesses the hydrological situation in the Sebeya Catchment and the methodology used to produce flood maps. The report presents hydrological data, such as a hydrograph from a flood event in March 2018. It further states that telemetry data is available from the Nyundo station from 2017, contradicting the information obtained for this thesis, c.f. Section 2.5.2. The report also states that rainfall data with 10-minute interval is available, further contradicting the data received from Meteo Rwanda for this thesis, which was only obtained as daily recordings.

The study was done in collaboration with a predecessor to RWB and included a 2-day-field visit at the beginning of 2018. The report presents concerns that the rainfall stations within the catchment are only located in the downstream area and may not represent the entire catchment well due to orographic effects. The flow data is statistically estimated at Nyundo and daily rainfall at Gisenyi for return periods between 5 and 1000 years and used for a HEC-RAS simulation; however, the simulation and bathymetry study were made several years before the flood mitigating infrastructure was constructed in 2020 and 2021. The report also states that mathematical validation of their model was not possible due to lack of data. The flood maps were compared to observations made by inhabitants of the catchment, the identified differences could be explained by discrepancies in the DEM, discrepancies in the cross sections and underestimating the flood discharges.

4.1.2. Hydrological Studies in Rwanda

A study conducted by Munyaneza et al. (2014) used a previous tracer-based study to compare to the model results obtained for the Level 3 Migina Catchment in southern Rwanda. For the modelling part the study used version 3.5 of HEC-HMS, with soil moisture accounting, unit hydrograph, linear reservoir and Muskingum-Cunge method. The HEC-HMS model was chosen because it has the ability to analyse spatially varied runoff generation characteristics, has a simple set up and limited data requirements as well as being a free software (Munyaneza, et al., 2014). The hydrographs were simulated for one year, as the catchment lacked reliable data for longer time periods the researchers used a hydrograph from a tracer-based study to compare the runoff components. They concluded that the model performed reasonably well with regards to total flow volume, peak flow and timing, and the portion of direct runoff and baseflow. The study by Munyaneza et al. (2014) is interesting as it used an alternative method to validate the results, as well as successfully model a catchment with very varied topography, the upstream slopes varied from 5 to 10 % and the downstream slopes were 1 to 21 %. The tracer study conducted by Munyaneza, et al. (2012) aimed to increase the hydrological knowledge in the Migina Catchment by hydrograph separation, i.e. surface and subsurface contributions to stream flows using isotopes and chemical tracers. It was found that 80% of the discharge during a rain event in the wet season came from subsurface runoff. In the Migina Catchment agricultural activities account for 92.5% of the land cover with 5% covered by forest (Munyaneza, et al., 2012).

Icyimpaye et al. (2022) created a HEC-HMS and HEC-RAS simulation with rainfall return periods of up to 100 years of the Nyabugogo Catchment using the Soil Conservation Service (SCS) Curve Number (CN) method and a rainfall timeseries of 30-years. The study did not discuss data quality and how the model was calibrated but focuses on proposing flood mitigating measures (Icyimpaye, et al., 2022). Niyonkuru et al. (2018) used a different model to simulate the stormwater runoff in the Nyabugogo Catchment – the Environmental Protection Agency's Storm Water Management Model (EPA SWMM). Using daily precipitation data and flow measurements for the period 1996 to 2017 they achieved a good fit between the simulated and measured data, including a validation and calibration period.

4.1.3. Climate Change Studies in Rwanda

Because Rwanda has a large diversity of agro-ecological zones due to its topography and climate it is difficult to establish an overall overview of how climate change will affect the country (Ministry of Environment, 2018). Prasad et al. (2016) used downscaled Global Climate (Circulation) Models (GCM) data for the four RCP scenarios and showed that the climate in Rwanda will in general become warmer, but that precipitation will be less affected. A projection of the year 2050 using the RCP 8.5 scenario showed a temperature increase of 2 to 2.5 °C and an increase in precipitation of 50 to 100 mm. The precipitation increase is assumed to be more than negated by higher evapotranspiration (Prasad, et al., 2016). The results of Asumadu-Sarkodie et al. (2015) showed a temperature increase of 2.7 °C in 2050 and 4 °C in 2080 as well as precipitation increase of 20 and 30 % respectively, causing the authors to conclude that both floods and droughts will be more common in the future. Umugwaneza et al. (2021) investigated how the Nyabugogo Catchment would be affected by climate change, by using downscaled GCM data for low and high emission scenario and the Soil and Water Assessment Tool (SWAT) to simulate the water balance in for the future periods of 2020-2050 and 2050-

2100. The evapotranspiration in the area was shown to be affected by the change in climate and under the most severe condition (SSP585) the surface runoff would increase by 3 % during the first period and decrease by 5 % during 2050-2100 (Umugwaneza, et al., 2021).

4.1.4. Missing Data and HEC-HMS Modelling

Estimating runoff response in ungauged catchments is a common problem in water resources management and hydraulic infrastructure construction, particularly in developing countries. Depending on catchment characteristics different methods can be used to solve this problem, e.g. extrapolating response information from gauged to ungauged catchments, remote sensing data, global hydrological models, unit hydrographs, coupled meteorological and hydrological models, regionalisation of model parameters and multiple regression (Meresa, 2019). Not all of these methods would be suitable for Sebeya Catchment, for example the surrounding catchments do not provide a better set of data and parameters such as topography or rainfall varies in the region.

If several flow measurement stations are located within a catchment or an area it can be possible to estimate missing data using statistical methods such as correlation and regression. Mfwango et al. (2018) conducted a study of the Great Ruaha Catchment in Tanzania where 11 gauging stations were available in the catchment with measurement history available between 16 and 24 years and data availability between 67 and 100 % (one station had a 100% data availability). They found Pearson’s correlation coefficients for the stations ranging between 0.4 and 0.9, with the stations closely located or on the same tributary river having higher correlation (Mfwango, et al., 2018). In a study by Elshorbagy et al. (2009) it was found that monthly and weekly hydrological data of the same river had higher autocorrelation than yearly and seasonal. Based upon this, Mfwango et al. (2018) chose five-year periods of complete datasets for two and three stations for linear and multiple regression analysis respectively to develop an equation to describe the datasets. The flows estimated through the developed equation was compared with the observed values through Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE), and mean absolute error (MAE). The results for the three stations with the highest correlation (data availability between 90 and 100 %) showed that the multiple regression analysis gave a very slight advantage to linear regression analysis during periods of high flow. However, a station that is a good estimator for one station is not necessarily a good estimator for another station, even when located on the same river. Mfwango et al. (2018) were less successful when using two stations approximately 60 km apart instead of two stations approximately 30 km apart, all located on the same river. The result was severely reduced when comparing stations on different tributaries, although located close within the catchment. The study also found that the recession method based upon the base flow was the best method to fill data during low flow periods and multiple regression was best during high flow periods.

De Silva et al. (2007) compared different methods of interpolating missing rainfall data for stations in Sri Lanka from surrounding stations. The methods were arithmetic mean, normal ratio, and inverse distance. De Silva et al. (2007) also introduced a new method which they called aerial precipitation ratio. They concluded that the best method to estimate missing precipitation data vary with the climatic zone as rainfall patterns and spatial distribution differs.

The HEC-HMS software has been used in several studies of various types of catchments in Africa and different types of available data. Ungauged catchments are catchments where the available hydrological data is not sufficient or of poor quality, thus making it difficult to create a hydrological model. To simulate the runoff and stream flow different methods can be used, such as using information obtained from gauged basins with similarities, using regional model parameters and hydrologic indices, remote sensing, or lab experiments (Tiwari, et al., 2018).

Olayinka-Dosunmu and Irivbogbe (2017) modelled the runoff in a small (28 km^2), urbanised, catchment in Lagos using HEC-HMS. Satellite data containing daily precipitation measurements for January to October for the years 2012 to 2017 and the Soil Conservation Services (SCS) method were used to construct event-based simulations for the years 2012, 2015 and 2017. However, as the area did not have any measurement stations their results are only compared to generally observed floods and their timings in the area and the validity of their model was based on previously conducted studies validating the HEC-HMS model.

A similar study was conducted by Tiwari et al. (2018) in which HEC-HMS was used to build a continuous model of the Hindon River Catchment. The river originates in the hilly lower Himalayan range in India and is entirely rainfed, subjected too monsoon conditions, and with the upper part of the catchments having low runoff potential due to the soil conditions. The aim of this study was to simulate the runoff for the ungauged part of the catchment, this was done using the SCS curve number (CN) loss method and gridded daily rainfall data obtained from remote sensing sources, and the simulation spanned over the years 2001 to 2010. Again, no validation process could be conducted due to the lack of observed data, however their result and conclusion is based upon the wide use of the SCS-CN method (Tiwari, et al., 2018). The SCS-CN loss method is based on empirical equations and runoff as a function of cumulative rainfall, soil cover, land use and antecedent moisture (Tiwari, et al., 2018).

Meresa (2018) used an Artificial Neural Network (ANN) method to model the non-linear input-output relationship between rainfall and runoff using remote sensing data from 1981 to 2017 for Keseke catchment in Ethiopia. The data used in the study was temperature, soil moisture, normalised difference vegetation index, and precipitation. Meresa (2018) found that the ANN method performed better than their HEC-HMS model in selected sub-catchments.

As described above, there are different statistical methods to estimate data or improve data quality for catchments such as Sebeya and software, like HEC-HMS, provides model approaches which are suitable to model data scarce catchments. Furthermore, remote sensing data can be used instead of relying on traditional measurement stations.

4.2. Site Visit and Interviews

The following section recounts the observations made during the site visit to the Sebeya Catchment in February 2022, as well as the interviews with residents and staff at local institutions. The purpose of the site visit was to compare collected geographical data with observations and to gather information about the recently constructed flood protection measures.

4.2.1. Accessibility within Sebeya Catchment

The Sebeya River is easily accessible between Mahoko and Gisenyi as the road is paved and mostly follows the river. Accessibility issues were encountered when the site visit group followed the river eastwards from Mahoko. On the second day the station at the Bihongora confluence could be reached, but on the third day the attempt to reach Bihongora for further studies had to be given up as the unpaved road had gotten to such a poor state that the pick-up truck could not manage to pass one of the hills. During the previous day at least one heavy truck loaded with rocks had been observed on the road and it was assumed that the traffic from the sand and rock mining at the confluence of Bihongora together with the rain the previous day had caused the road condition to deteriorate. The site visit focused on the area between Gisenyi and Mahoko and towards the southeast of the catchment. Figure 4-1 shows that the road network outside of the main villages is poor, especially the area labelled as “Gishwati Forest Reserve”, the upstream area of Sebeya barely have any roads and is likely only accessible by foot or motorbike.

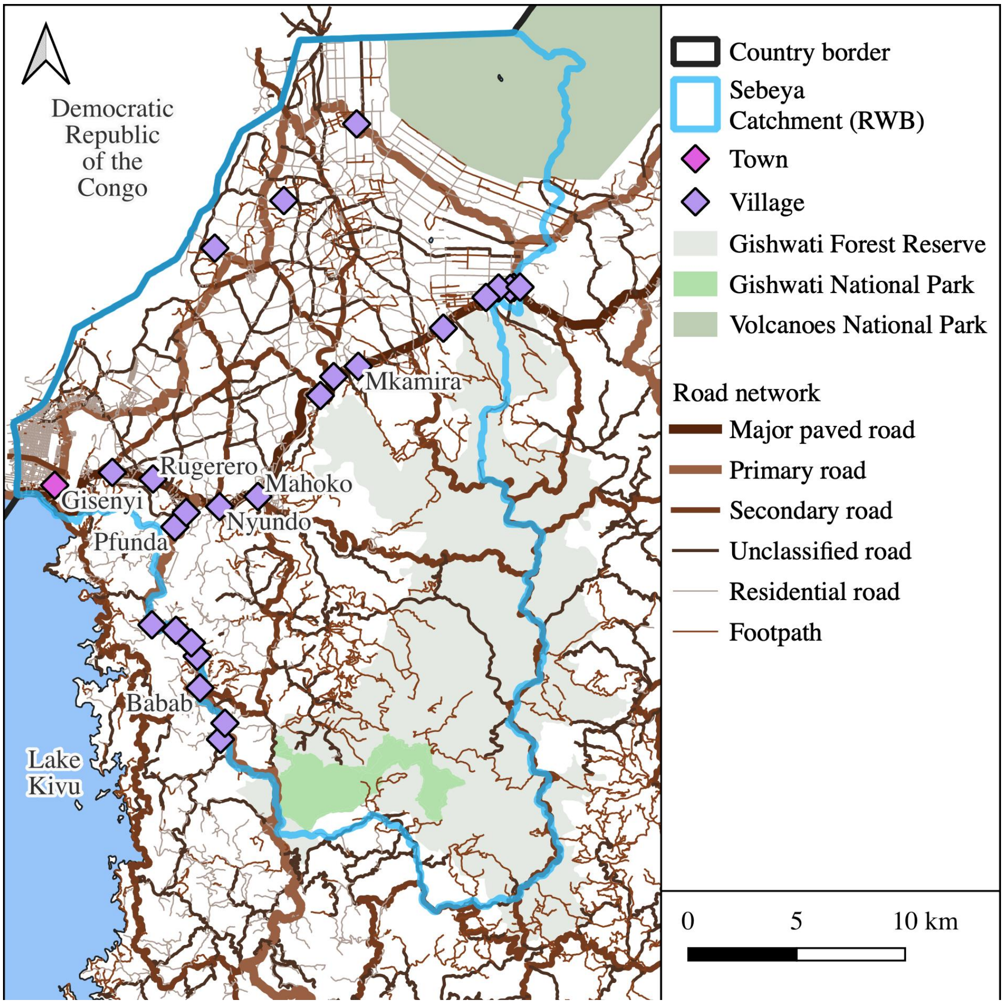


Figure 4-1 Road network in Sebeya Catchment.

4.2.2. Flood Protection Measures and Land Use along the Sebeya River

A lateral dike with a flood retention area was located outside of Mahoko, the construction of it started in 2020 and it was completed in 2021. It was observed that a high amount of sediment had been deposited by the Sebeya River and amassed at the inlet. According to the caretaker of the dike, the depth before and after the inlet had been between 0.5 and 1.0 metre at the completion. At the time of the visit the dike had been completed for approximately one year and the sediment deposits were at the same level as the top of the inlet, shown in Figure 4-2. The flood retention area utilises a field, a former tea plantation, that naturally floods during high flows, seen in Figure 4-3, while the outlet is seen in Figure 4-4. The design is described in the unpublished design document by Water for Growth Rwanda (Water for Growth Rwanda, 2020a).

Figure 4-2 Sediment deposits at the inlet of the Sebeya lateral retention dike at Mahoko.


Figure 4-3 Flood plain at Sebeya lateral retention dike.


Figure 4-4 Outlet at Sebeya lateral retention dike.

In Nyundo and Mahoko sandbags were used as flood protection. Most of them had been there for one to two years and already showed signs of deterioration, as can be seen in the right part of Figure 4-5. Bamboo is planted as the roots retain the soil and hinders it being flushed away during floods. Sandbags and bamboos were mostly seen to protect footpaths and roads close to the river against erosion or to curb the flooding of flatter, low-lying areas. At more sensitive stretches of the river, e.g. where the river flows close to the main paved road, the embankments were reinforced by gabion retaining walls.

Figure 4-5 Bamboo and sandbags along the Sebeya River.

Some parts of the Sebeya River, by the villages Nyundo and Mahoko, and the Pfunda River by the confluence, had been straightened, but for the most part it appeared to follow its natural course. Smaller foot bridges are present along the river, many are made of wood and, according to residents, they were often damaged or destroyed during increased flows and floods. Following the Sebeya River upstream from Mahoko towards the Gishwati Forest, recently completed and currently constructed terraces were observed on many of the hills, see Figure 4-6.

Figure 4-6 Terrace construction by Sebeya River.

At the Karambo confluence and in Mahoko large and newly constructed retaining walls could be seen. The design of the wall at Karambo is described in the report Gisunyu-Karambo Protection Wall (Water for Growth Rwanda, 2020c). In Mahoko the retaining wall was constructed on the northern embankment of Sebeya, Figure 4-7. Most of the village is located north of the river.

Figure 4-7 Retaining wall in Mahoko Village.
In the photo grey ellipses are used for anonymisation.

Between Karambo and Bihongora the construction was about to start on a new dam across the Sebeya River. Figure 4-8 shows the location, seen from the Rusongati Mountain and the dam is described in the report Sebeya Retention Dam – Phase 3 Detailed Design (Water for Growth Rwanda, 2020b).

Figure 4-8 Construction site of the Sebeya retention dam.

Mining activities were primarily observed at the Bihongora confluence (excavation in the river and embankments) and next to the Pfunda confluence. At the Bihongora confluence there was intense activities with several trucks, excavators, and staff working at the time of the visit. Along the Sebeya River individuals could also be observed collecting rocks and sand in minor quantities. The area north of Mahoko and Nyundo was not visited during the field trip, thus the diversion channels at Bukeri from the fourth design report (Water for Growth Rwanda, 2020d) received from RWB could not be observed.

Three small hydropower plants were visited, located outside Nyundo (Keya HHP), Rugerero (Gihira HPP) and Gisenyi (Gisenyi HPP). All of them have gated inlets deviating the water from the river and channels for sediment deposition. The penstocks, approximately one kilometre in length, were visible for the Keya and Gisenyi HPPs. The turbine and generator houses can be identified for Keya and Gisenyi HPPs using Google Maps. The power plants have an available capacity of 0.87 MW in Gisenyi HPP, 1.26 MW in Gihira HPP, and 1.1 MW in Keya HPP (Hakizimana, et al., 2020). The powerplants also have dams blocking the flow but they were barely visible as the river was overflowing the dams due to high water levels at the time of the visit. One water treatment plant was seen outside Rugerero (Gihira WTP).

4.2.3. Interviews

Ten interviews were conducted during the field visits, and the locations are shown in Figure 4-9, with the number in bracket representing the interviewees estimate of the largest flood they have experienced in in the area.

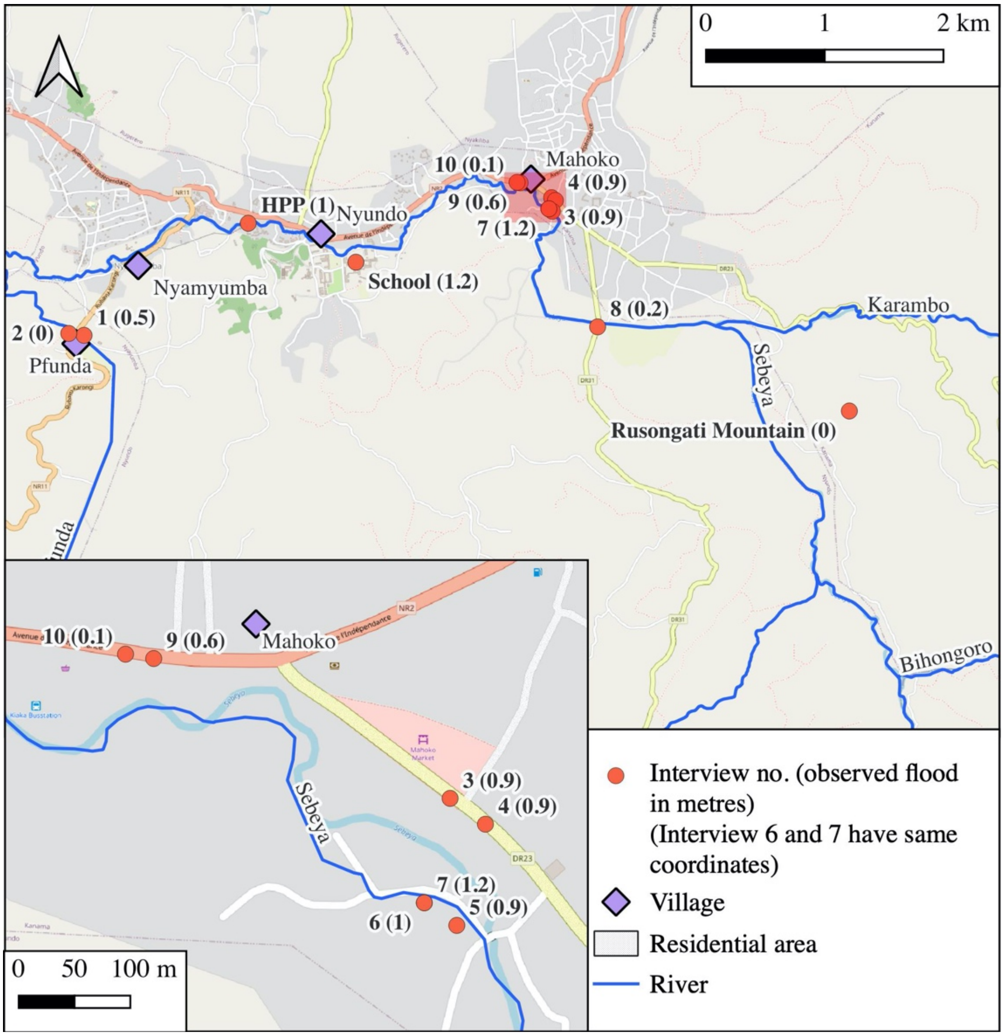


Figure 4-9 Interview locations and observed flood heights.

4.2.3.1. Residents in Sebeya Catchment

Seven of the interviewees had once or multiple times experienced flooding of their homes. Although the period since the completion of the dike and retaining wall in 2021 has been too short to draw conclusions, nine interviewees said that the village had been less affected by floods after the completion of the dike. There was a consensus between all the interviewed residents living north of Sebeya River in Mahoko in that their houses had not been affected by floods after the dike and retaining walls were built in Mahoko. All the interviewees living south of the river would like a higher retaining wall or measures to be implemented to protect the southern river embankments as they are still affected by the floods. None of the interviewees had been affected by landslides. Not all the interviewees had prepared for floods, the ones that had had used sandbags, but had found them to be useless during large floods as the water washed them away. There is no official warning system, some residents have sometimes been warned via phone by people they knew living upstream. There is not always time to warn as the floods can occur during night or as flash floods. The interviews are summarised in Table 4-1.

Table 4-1 Summary of interview responses.

Interview no.	Maximum experienced flood height (m)	Date of flood	Flood impact
1	0.5	May 2021	Destroyed their home and crop fields. Interviewee lives on the north-eastern side of Pfunda, south of Sebeya. The flood came from Sebeya.
2	0	-	Had not experienced any floods, interviewee lives on the south-western side of Pfunda towards the hills seen in Figure 4-18.
3	0.9	April 2019	Destroyed home and crop fields.
4	0.9	June 2018	Destroyed home and crop fields.
5	0.9	April 2010	Damaged home and client clothes (seamstress).
6	1.0	May 2020	Their house collapsed and neighbour died.

7	1.2	May 2021	Water entered their house
8	0.2	2020	Interviewees own house has not been affected.
9	0.6	May 2018	Restaurant owner had his property damaged to an estimated value of 1 million RWF (approx. 1,000 EUR)
10	0.1	May 2019	Interviewee's house is elevated compared to Interview 9's neighbouring house.

4.2.3.2. Keya Hydropower Plant

The water intake, dam, and office building of the Keya Hydropower Plant (HPP) is located on the southern border of the Sebeya River just outside Nyundo, the turbine is located close in Nyamyumba. The supervisor of the Keya HPP was interviewed as the plant experienced severe flooding in 2018. The supervisor described the following:

The flood damaged a small bridge, the office and the fence, the flood was estimated to have reached a height between 0.8 and 1.0 meter around the office building. Due to the flood the hydropower plant had to be shut down for five days. To protect against future flooding the following measures were implemented:

- *Retaining walls constructed using gabions*
- *Bamboo was planted to stop soil erosion*
- *Sandbags*
- *The bridge was reconstructed*

To further improve flood protection, the supervisor recommended the following:

- *Constructing more hydropower plants upstream that could hold more water*
- *Constructing more dams upstream to hold more water and sediment (sediments causes operating issues for the hydropower plants in the area)*
- *Planting more bamboo*
- *Creating more terraces*

Figure 4-10 shows the power plant when it had closed its inlet to protect the turbines from the large amounts of sediments in the water and to remove previously deposited sediments. The supervisor explained that the inlet often is closed to protect the turbines.

Figure 4-10 Sediment deposits in HPP channels.

4.2.3.3. Secondary School - Petit Seminaire Saint Piex de Nyundo

The school is located in Nyundo on the southern embankment of the Sebeya River. The school was severely damaged during a flood in March 2018 and a school secretary who had worked at the school during the flooding was interviewed for this report. She recounted the following:

School infrastructure and equipment (computers, projectors, desks), and students' beds and properties were damaged. Even the water tanks were damaged as the water came with such force that they were knocked over, the water tanks were previously located in the school yard. The flood level around the school buildings were approximately 1.1 metres.

The flood wave had come during the early morning and without warning, the rain in the local area had not been noticeably heavier. Afterwards it became known it had been raining heavily in the Gishwati Forest, the water had accumulated and eventually been released creating the flood wave in the downstream area of Sebeya. Several people died because they were mining sand in the river at the time of the flood.

To reduce impact of future floods the authorities straightened and widened the Sebeya River close to the school, built retaining walls, sediment deposits were removed in the river to improve the flow and bamboo planted to retain the soil on the river embankments. Since the hydraulic measures and the dike was built the smaller floods which were commonplace has not happened.

4.2.3.4. At the top of Rusongati Mountain

A resident of the Rusongati Mountain, located between the Bihongora and Karambo confluences, guided us up the hill to get an overview of the Sebeya River in that area. He also explained the following:

The government had during the last two years paid landowners to convert their agricultural fields on the hills to terraced fields. This had resulted in increased crop yields as the water is retained at the different levels as well as reducing the runoff to the river during heavy rainfall. It would not have been possible for the farmers to convert the land if the government had not subsidised the cost. Authorities had also been planting trees to retain the soil and reduce landslides.

4.3. Data Evaluation for Hydrological Modelling

The following section presents the hydrological and meteorological data that was collected and the evaluation of data for use in the HEC-HMS model and map creation.

4.3.1. Geographical Data

The DEM30 was found to be suitable for catchment delineation in QGIS as it was not missing any data and had been quality checked by the publishers. An unpublished DEM file with 10 metres resolution was obtained from RWB, unfortunately this file proved to be missing a substantial amount of data, approximately one third of the Sebeya Catchment, and was therefore discarded.

The river network was burnt into the DEM file to provide a better fit to the real course of the rivers. The river network shapefile obtained from RWB's GeoPortal only includes perennial streams and was better corresponding to the observations made during the site visit than similar layers obtained from Open Street Map and ArcGIS Hub.

The settlements, cities, and villages shapefiles were obtained from Open Street Map/ArcGIS Hub (ArcGIS Hub, 2020b). The settlements layer is incomplete around the Mahoko and Nyundo area and not corresponding well to observations made during the site visit.

4.3.2. Hydrological Data

Refer to Section 2.5.2 for a list of the hydrological data used in this report. The daily data series had significant gaps, primarily between 1989 and 2018. Meanwhile, the telemetry data does not date further back than 2018. For the locations of the stations, refer to Figure 4-11 which depicts the hydrological stations observed on the field trip. Only one decommissioned station was found at the Gisenyi outlet, and it was not clear if it had been the Gisenyi-Sebeya or Gisenyi-Kivu station. At the time of the visit, the equipment was missing at the Nyundo station – according to the local caretaker it had been stolen. The newly installed telemetry stations at Pfunda, Mahoko, Karambo and Bihongora were all observed during the site visit.

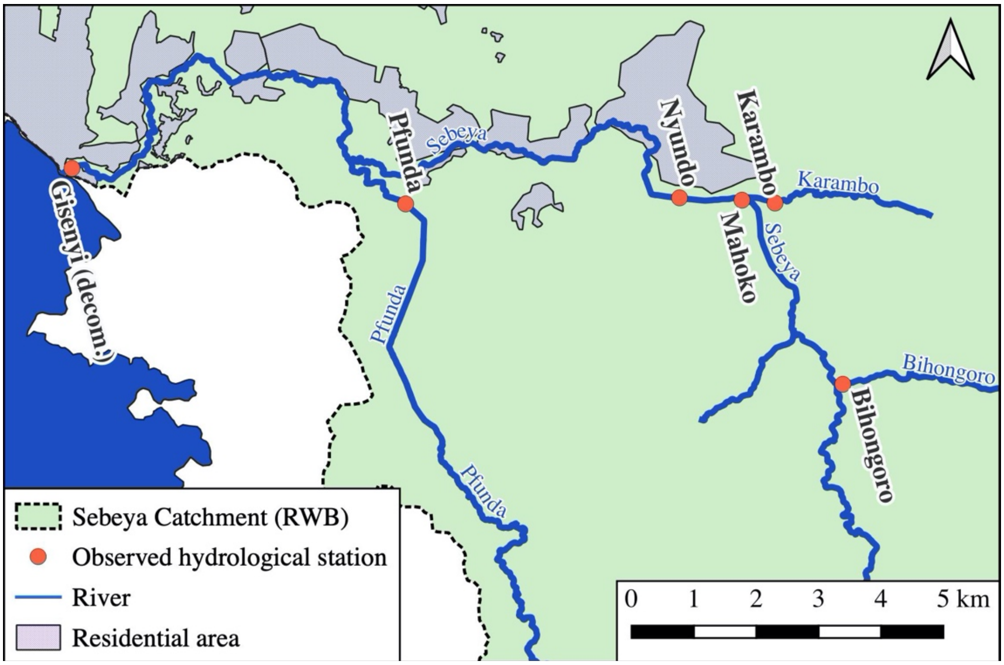


Figure 4-11 Observed hydrological stations in Sebeya Catchment.

The telemetry data from the Nyundo station showed good correlation between the stage and discharge, the data recorded between 1st of August 2020 and 29th of November 2021 has a correlation of 0.90, illustrated in the scatter plot in Figure 4-12. Note that the trendline does not intercept the origin, as would be expected.

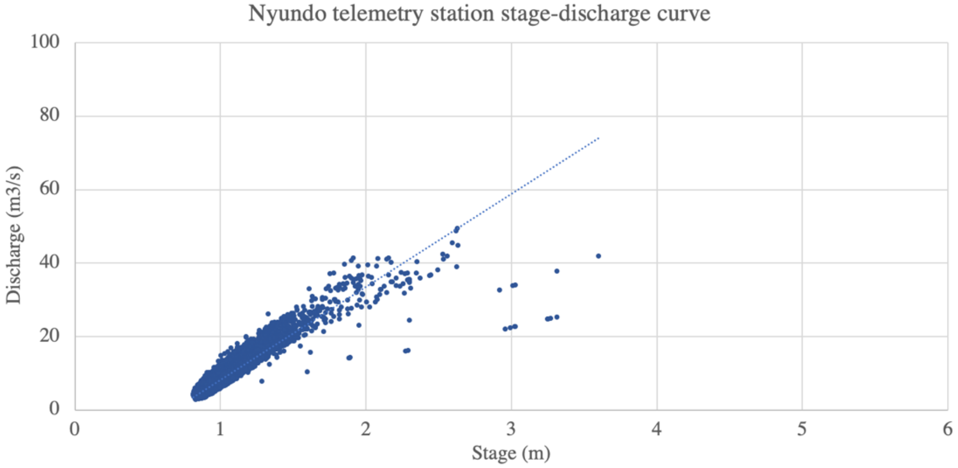


Figure 4-12 Scatter plot of stage and discharge for Nyundo telemetry data.

The Nyundo telemetry station is located along a stretch of the Sebeya River with stone retention walls. When comparing the area observed during the site visit to the photos in the design document for the lateral retention dike (Water for Growth Rwanda, 2020a), it can be seen that the cross section and sides of the river has changed during construction of the dike. The construction of the dike occurred between 2020 and 2021, the same period as the telemetry data were recorded. Thus, the river profile could have been altered and it is unclear if this has affected the discharge data. The outlet of the retention dam is located closely upstream of the measurement station and is likely affecting the readings. Furthermore, as the station is located just upstream of a bridge, this could cause backwash effects on the stage, and it is not clear if the data is calibrated for those effects.

Figure 4-13 Nyundo telemetry station.

For the other station in Nyundo – the Nyundo daily station – the correlation coefficients between the stage and discharge values obtained are low – 0.24 for the data from 1974 to 1989 and 0.14 for the years 2009 to 2013, illustrated by the scatter plot in Figure 4-14. Thus, the data from the Nyundo daily station is not considered to not be reliable for rainfall-runoff modelling.

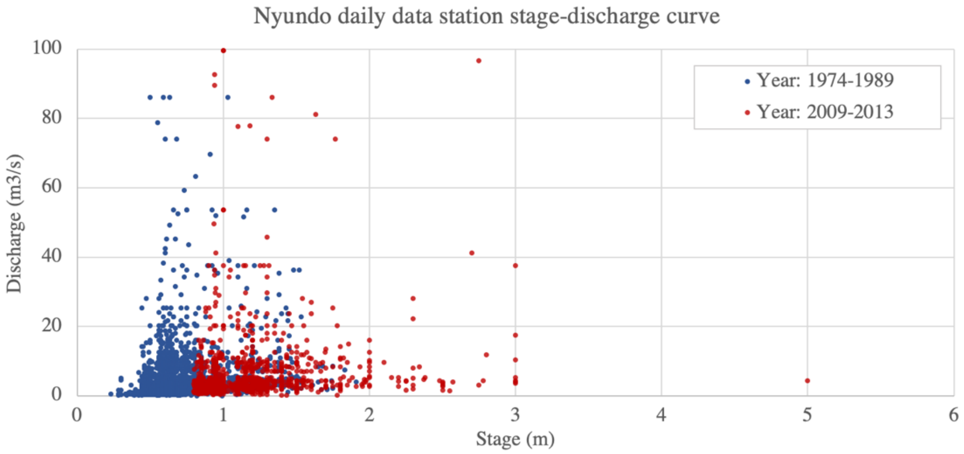


Figure 4-14 Scatter plot of stage and discharge for Nyundo daily data.

Figure 4-15 shows the stage-discharge curves for the daily data for the Gisenyi-Sebeya station. There are not enough measurements to identify any clear relationships, and it can also be observed that the relationship has changed over the course of time. This is likely due to a changing river profile, as the station was placed at a section of the river impacted by erosion, see Figure 4-16.

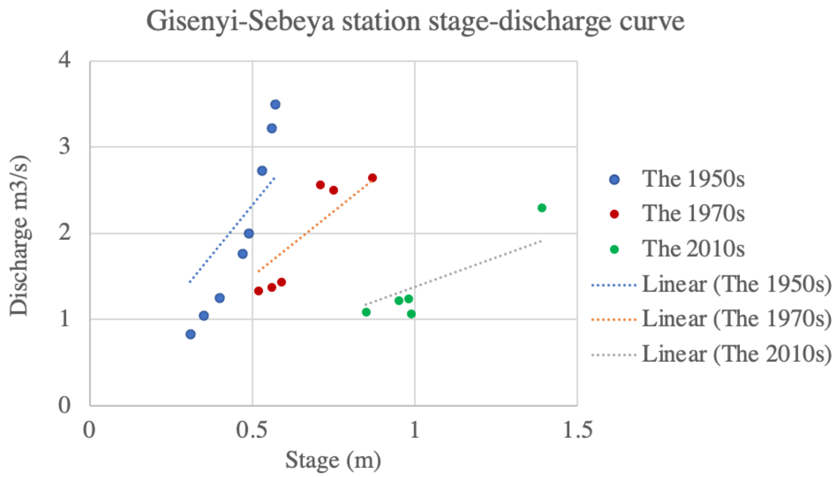


Figure 4-15 Scatter plot of stage and discharge for Gisenyi-Sebeya daily data.

Figure 4-16 Decommissioned station at Gisenyi.

The stage-discharge measurements for the Pfunda and Bihongora stations are shown in Figure 4-17, there are too few measurements to construct reliable curves and the ranges of stage measurements is low, between 0.2 and 0.35 metre for the respective stations. Figure 4-18 shows the location of Pfunda station, it is located just upstream of a bridge. See Appendix for photos of the Karambo and Bihongora stations, both are located at locations with unstable embankments and river profiles.

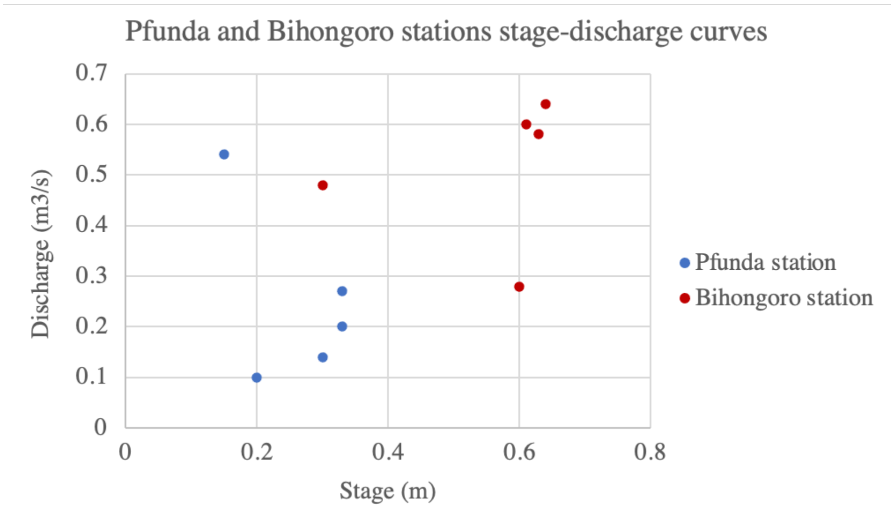


Figure 4-17 Scatter plot of stage and discharge for Pfunda and Bihongora telemetry data.

Figure 4-18 Hydrological measurement station and tea plantation at Pfunda confluence.

Table 4-2 shows the reason for discarding data sets and the amount of missing data for data sets with rating curves. Discharge measurements or estimations are required for the HEC-HMS model and rating curves are used to convert a stage recording to an estimated discharge.

Table 4-2 Hydrological data evaluation.

Station name	**Type**	**Reason for discarding the data**	**Missing data (%)**	**Suitable for HEC-HMS model**
Gisenyi-Kivu	Daily (stage)	No rating curve		No
Nyundo	Daily (stage, discharge)	Low correlation between stage and discharge data		No
Gisenyi-Sebeya	Daily (stage)	Poor rating curves, missing data	55 (mainly between 1989 and 2011)	No
Nyundo	Telemetry (stage, discharge)	Stage data has high amount of missing data	20 (stage, mostly before August 2020) <1 (discharge)	Yes (discharge)
Karambo-Mahoko	Telemetry (stage)	No rating curve, short recording period		No
Pfunda	Telemetry (stage)	Poor rating curve		No
Sebeya-Mahoko	Telemetry (stage)	No rating curve		No
Karambo	Telemetry (stage)	No rating curve, short recording period		No
Bihongora	Telemetry (stage)	Poor rating curve		No

The only suitable data set to use for the HEC-HMS model was determined to be the Nyundo telemetry discharge data available from 01-08-2020 to 29-11-2021. The time series for this station is shown in Figure 4-19. Detailed data results are shown below.

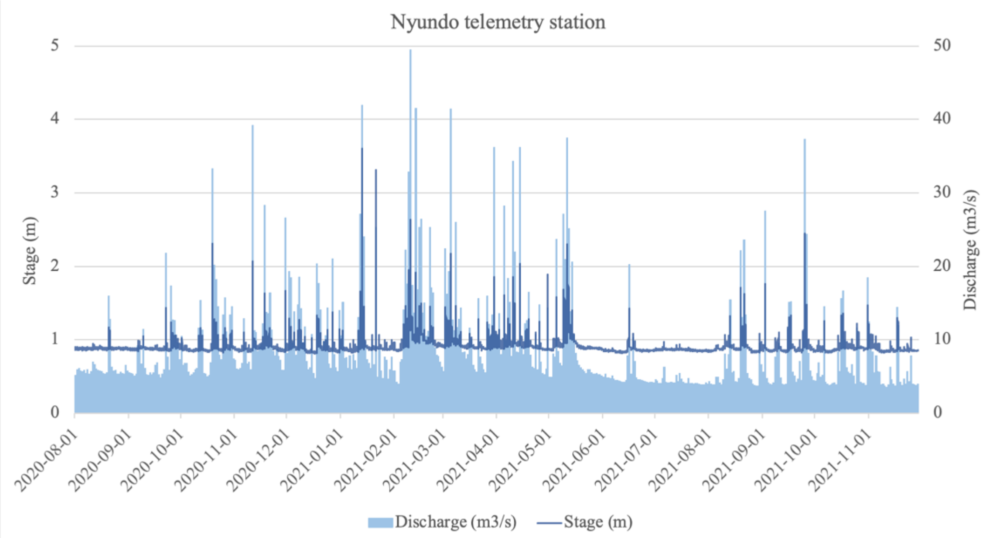


Figure 4-19 Nyundo telemetry stage and discharge timeseries.

4.3.3. Meteorological Data

Data were received from Meteo Rwanda from the stations mapped in Figure 4-20 (turquoise dots). The magenta dot shows a meteorological station that was observed during the site visit; however, the location does not match the coordinates of any of the stations from Meteo Rwanda. Figure 4-21 shows the average monthly precipitation in millimetre for the nine meteorological stations. The two dry seasons, December to February and June to August, as well as the two wet seasons, March to May and September to November, are easily identified in the graph. The stations are listed in the order of most eastern (Kibisabo) to most western (GisenyiAero). A pattern emerges in the graph in Figure 4-21 which corresponds to Seibert (2019), i.e. a heavier rainfall during the wet season at the stations located in the eastern, hilly area compared to the stations located closer to Lake Kivu in the western parts. Thus, data from the GisenyiAero station may underrepresent the amount of rain falling in the eastern area of the catchment. However, care should be taken to draw any certain conclusions as some data sets are both limited in duration and missing large amounts of recordings. It should also be noted that the Muhungwe data set only has 34 readings over the two available December months.

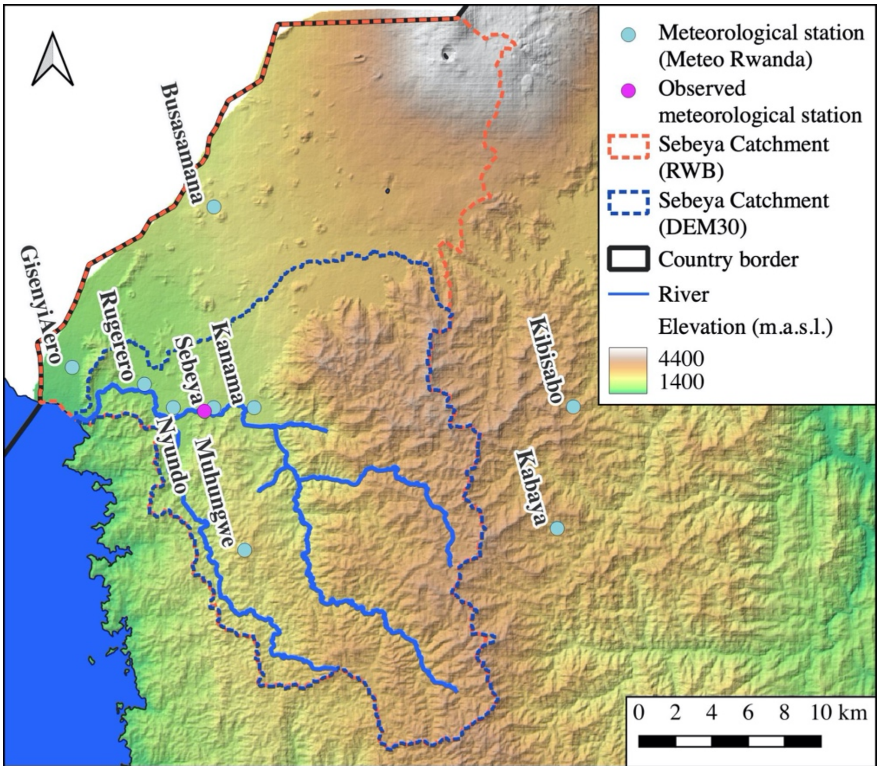


Figure 4-20 Meteorological stations in and around Sebeya Catchment.

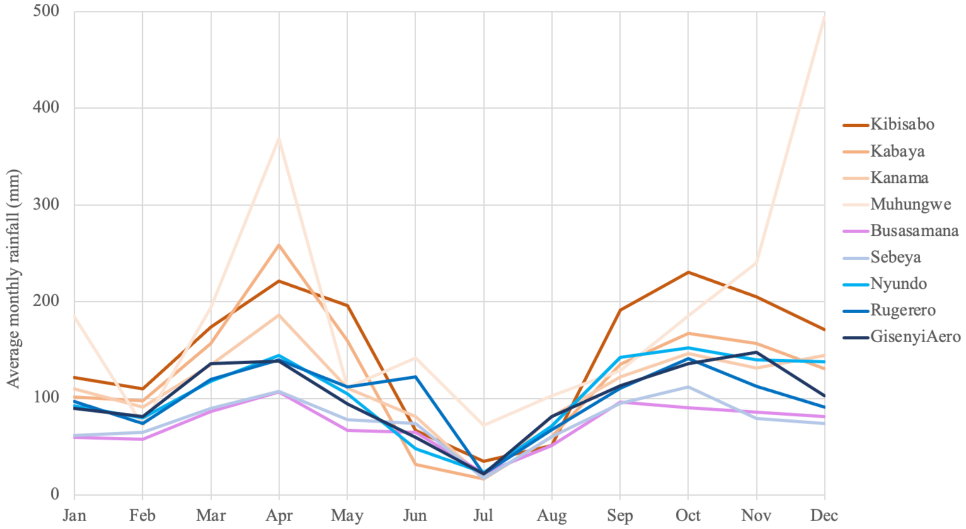


Figure 4-21 Average monthly precipitation for each station.

Some of the meteorological timeseries were found to have large amounts of missing data as shown in Table 4-3. The Kibisabo and Muhungwe stations were excluded as they did not have recordings corresponding to the period of the chosen hydrological timeseries. The stations that were selected to be suitable for the modelling were GisenyiAero, Nyundo, Kabaya, and Kanama The corresponding timeseries of the selected stations are presented in Figure 4-22. GisenyiAero was chosen to be used for the hydrological modelling as corresponding data were available for flow, temperature, and relative humidity.

Table 4-3 Meteorological data evaluation.

Station name	**Data**	**Missing data (%)**	**Suitable for HEC-HMS model**	**Reason for discarding data**
GisenyiAero	Rainfall Temp. (min) Temp. (max) Relative humidity	0*	Yes, but station is outside delineated catchment (DEM30)	
Nyundo	Rainfall	0*	Yes	
Kabaya	Rainfall	5	Yes	
Busasamana	Rainfall	27	No	Missing data
Kanama	Rainfall	5	Yes	
Sebeya	Rainfall	29	No	Missing data
Rugerero	Rainfall	18	No	Missing data
Kibisabo	Rainfall	9	No	Wrong period
Muhungwe	Rainfall	23	No	Wrong period, missing data

** It is not clear whether the data received for GisenyiAero and Nyundo had been checked for errors, filled in or if recordings of 0 mm also meant missing data.*

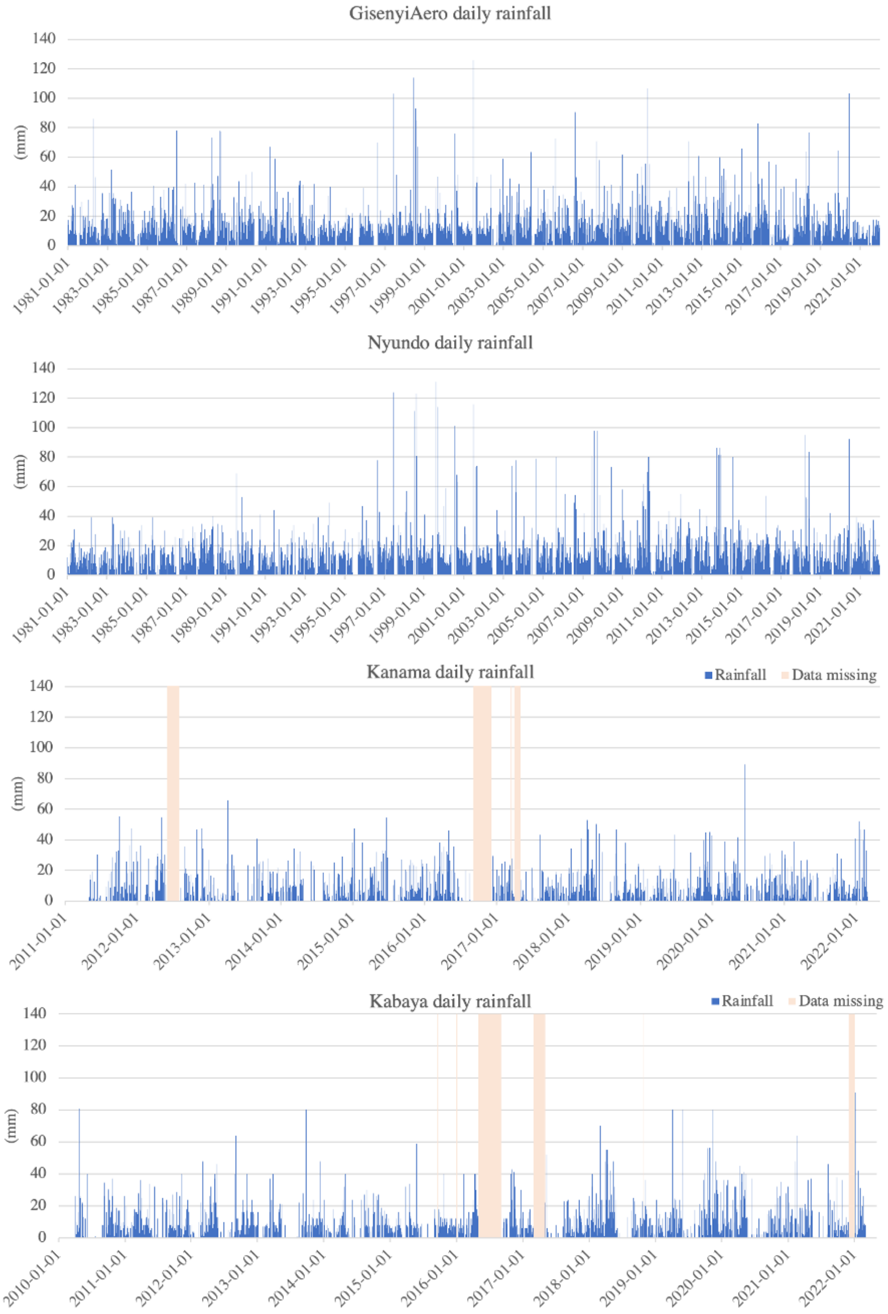


Figure 4-22 Rainfall timeseries for selected stations.
Note the different timescale for each station.

4.4. Rainfall-Runoff Modelling

4.4.1. Catchment Delineation

The two methods of delineation described in Section 2.4.1 gave almost identical results. Burning in the river network gave a more accurate location of the streams created using the DEM30, however, the outer boundaries of the catchment remained the same. The delineated catchment shown in red in Figure 4-23 was created using Method 2, which included the SAGA and GRASS toolset in QGIS and having the rivers burnt into the raster at 10 metres depth, as this gave the best result for the river network when compared to site observations and Open Street Map.

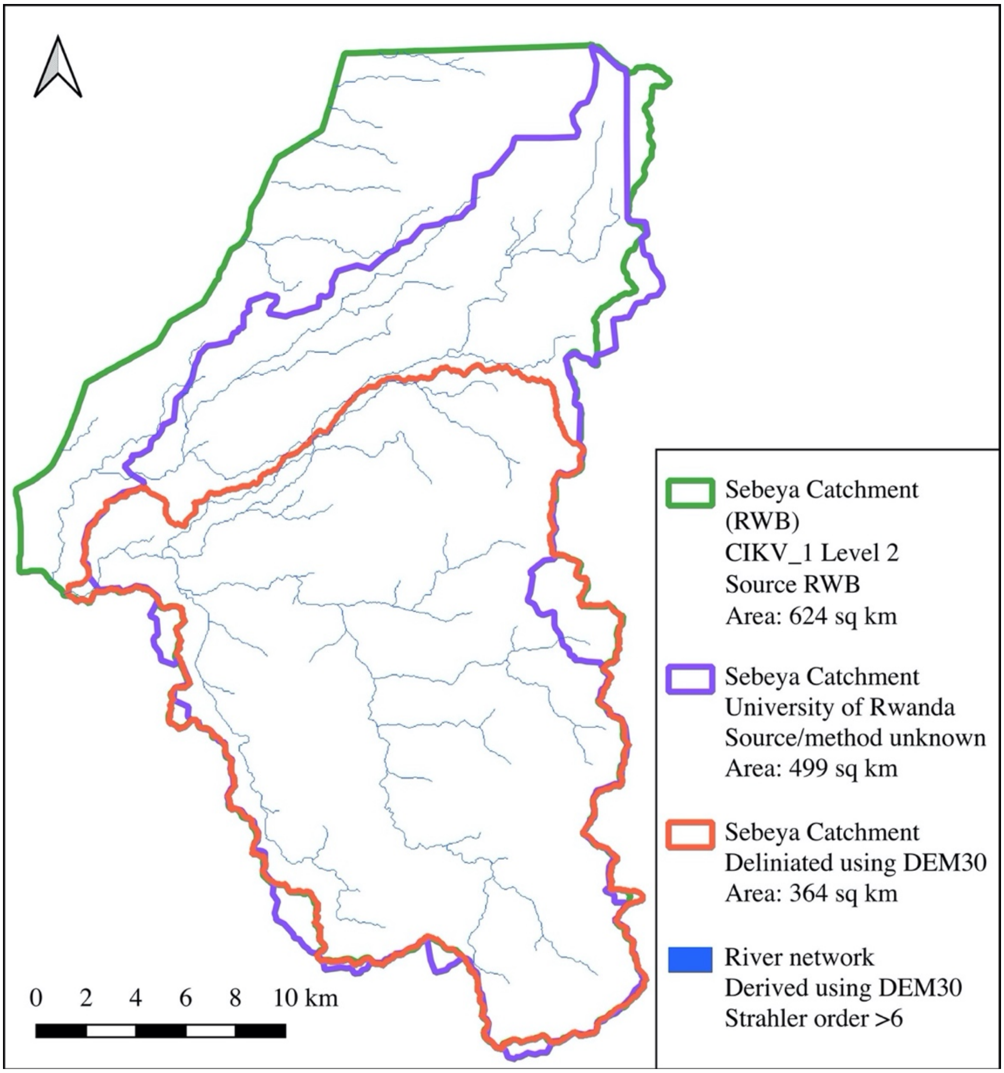


Figure 4-23 Map showing three versions of the Sebeya Catchment.

Several areas are referred to as Sebeya Catchment by different entities and reports. The area used in the Rwanda National Water Resources Master Plan (MINIRENA-RNRA, 2015) and referred to as "CKIV_1" by RWB on their online web portal is in this report called "Sebeya Catchment (RWB)". The delineated area in this report closely matches the area pictured in Sebeya Catchment Management Plan (Ministry of Environment, 2018) and is thus referred to as “Sebeya Catchment” or “Sebeya Catchment DEM30” in this report. In the Sebeya Catchment Management Plan the area of Sebeya Catchment is stated to be 336 km^2, which is close to the delineated catchment area of 364 km^2 as calculated in QGIS. A third catchment boundary, pictured in Figure 4-23 in purple, was obtained from contacts at University of Rwanda. The original source or delineation method is unknown, and it matches neither the version used by RWB nor the version delineated using the DEM in QGIS, thus, this catchment area is not considered further in this thesis.

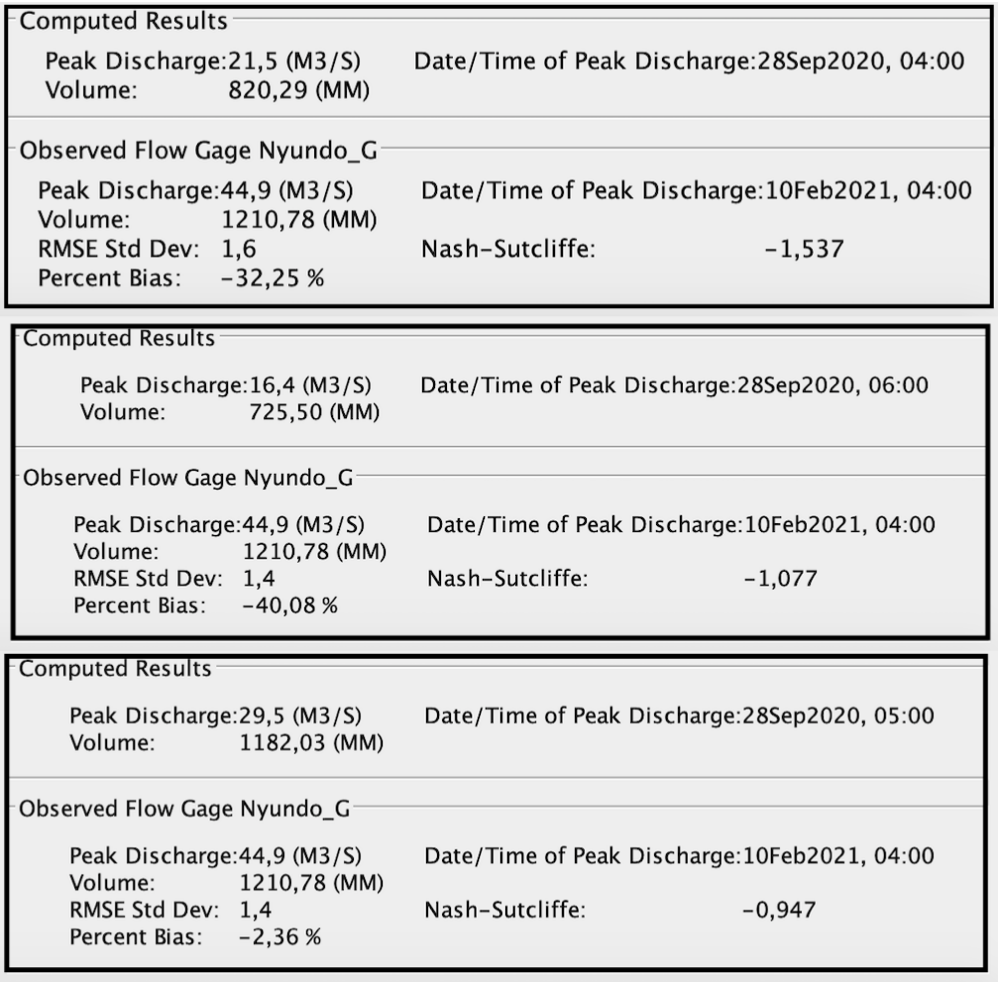
4.4.2. HEC-HMS Model

The sub-catchments upstream of Nyundo telemetry station were modelled in HEC-HMS using a continuous model, for a map of the basin model see Figure 2-3. Two iterations of calibration were conducted on the rainfall-runoff model, the steps are presented in Table 4-4.

Table 4-4 Calibration of HEC-HMS model.

Method	Parameter	Change
	First calibration iteration	
Loss – Deficit and Constant	Initial deficit	From 5 mm to 30 mm
Transform – Clark Unit Hyd.	Time of concentration	T_c multiplied by factor of 2
Baseflow – Linear reservoir	Groundwater coefficient 1 and 2	Both GW1 and GW2 multiplied by a factor of 3
	Second calibration iteration	
Loss – Deficit and Constant	Constant rate	Changed from 5 mm/h to 1mm/h
Baseflow – Linear reservoir	Initial type, GW1/GW2 Initial	Initial type changed to “discharge”, GW1/GW2 Initial set to $2m^2/s$ for all sub-basins
Transform – Clark Unit Hyd.	Storage coefficient	R set to 0.5 h for all sub-basins

Figure 4-24 shows the change in peak discharge, volume, and Nash-Sutcliffe value. The top box shows the metrics using the initial model values specified in Section 2.4.2.1, the middle box is after the first calibration and the bottom box shows the metrics after the second and final calibration iteration. The final model has a computed volume closer to the observed volume, however the computed peak discharge is only 65% of the observed peak and on a different day. The Nash-Sutcliffe value is below the satisfactory 0.5. A negative Nash-Sutcliffe value indicates that the mean of the observations is a better predictor than the model (USACE HEC, 2023).



```
Computed Results
  Peak Discharge:21,5 (M3/S)     Date/Time of Peak Discharge:28Sep2020, 04:00
  Volume:          820,29 (MM)

Observed Flow Gage Nyundo_G
  Peak Discharge:44,9 (M3/S)     Date/Time of Peak Discharge:10Feb2021, 04:00
  Volume:          1210,78 (MM)
  RMSE Std Dev:    1,6           Nash-Sutcliffe:                 -1,537
  Percent Bias:    -32,25 %
```

```
Computed Results
  Peak Discharge:16,4 (M3/S)     Date/Time of Peak Discharge:28Sep2020, 06:00
  Volume:          725,50 (MM)

Observed Flow Gage Nyundo_G
  Peak Discharge:44,9 (M3/S)     Date/Time of Peak Discharge:10Feb2021, 04:00
  Volume:          1210,78 (MM)
  RMSE Std Dev:    1,4           Nash-Sutcliffe:                 -1,077
  Percent Bias:    -40,08 %
```

```
Computed Results
  Peak Discharge:29,5 (M3/S)     Date/Time of Peak Discharge:28Sep2020, 05:00
  Volume:          1182,03 (MM)

Observed Flow Gage Nyundo_G
  Peak Discharge:44,9 (M3/S)     Date/Time of Peak Discharge:10Feb2021, 04:00
  Volume:          1210,78 (MM)
  RMSE Std Dev:    1,4           Nash-Sutcliffe:                 -0,947
  Percent Bias:    -2,36 %
```

Figure 4-24 HEC-HMS computed model metrics.
Top box summarises the metrics for the result using the initial parameter values, the middle box shows the metrics after one calibration iteration and the bottom box shows the metrics after the final calibration.

Figure 4-25 shows the resulting hydrographs of the model produce in HEC-HMS, representing the part upstream of Nyundo of the Sebeya Catchment. The top graph is based on the initial parameter values, the middle graph is after one calibration iteration, the bottom graph is after second iteration. The blue lines represent the computed values at Nyundo and the black lines represent the values observed by the Nyundo telemetry station. It can be noted that the calculated base flows, especially during dry periods, are lower than the observed values. The timing and magnitude of the peaks is also a poor fit. The timeseries was too short for a continuous model as it was not possible have a warm-up period, a calibration period, and a validation period of several years each.

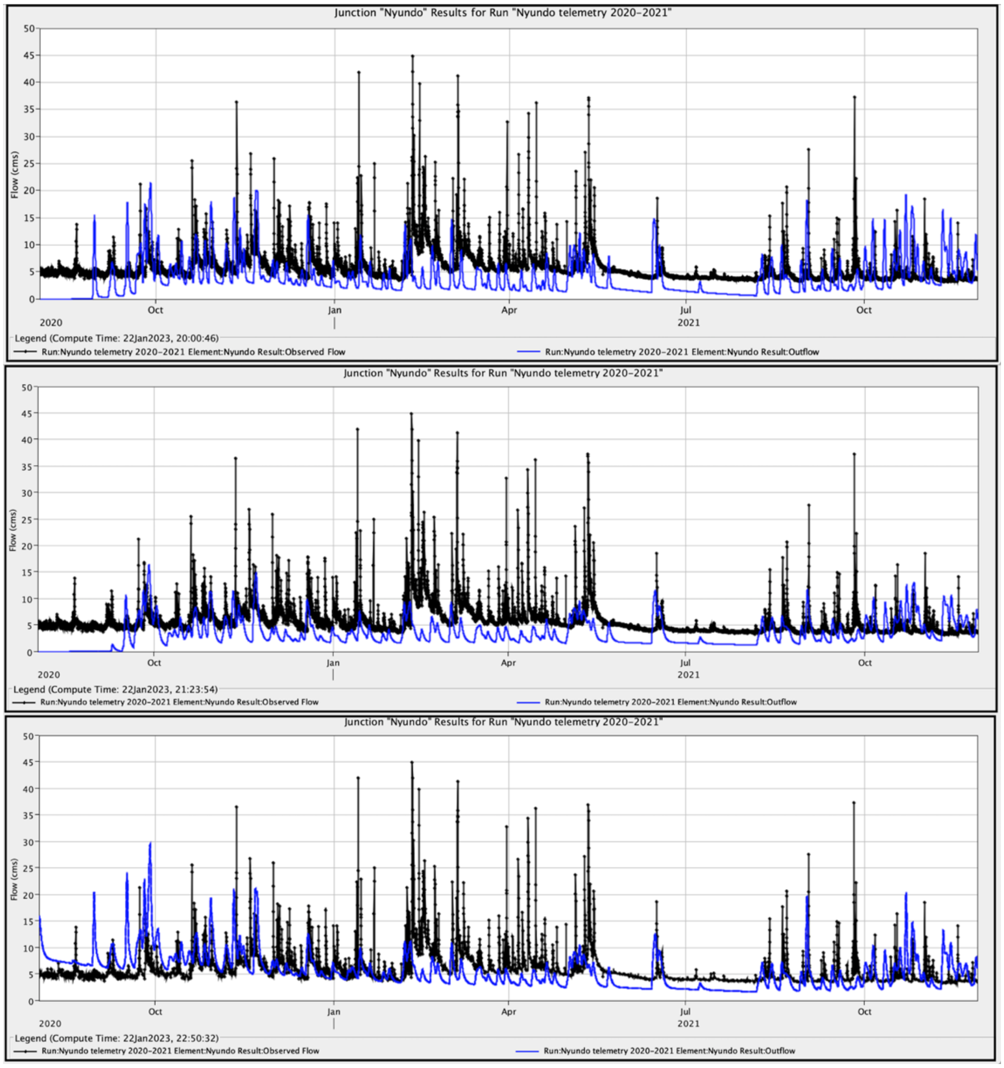


Figure 4-25 HEC-HMS results.

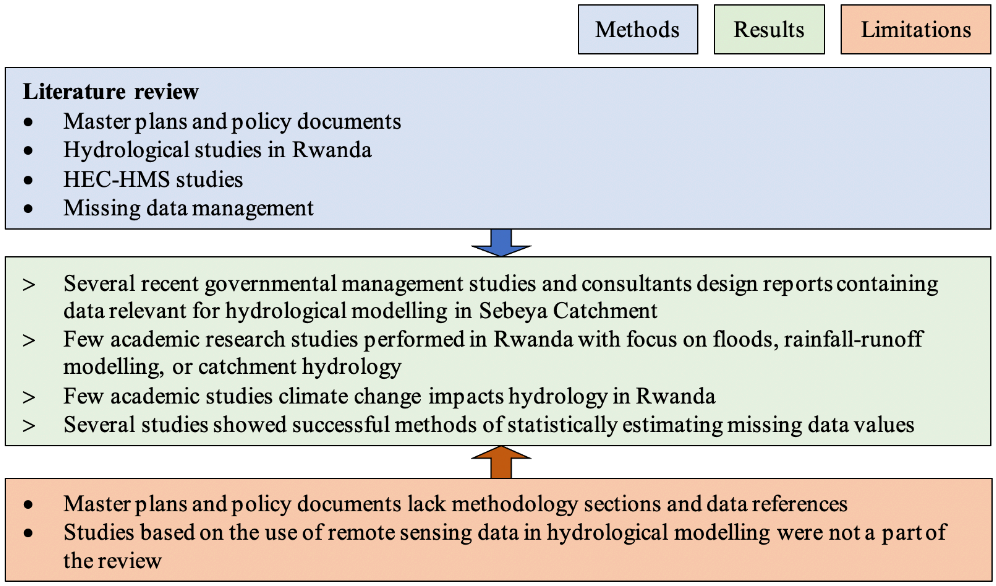
Top graph shows the results based on the initial parameter values, the middle graph shows the results after the first calibration and the bottom graph show the results after the second and final calibration.

5. Discussion

The following section discusses the results obtained for the different parts of this report as well as their limitations.

5.1. Existing Literature

The master plans, policy documents, and design documents are informative and often include site visits, geological studies, or field measurements, however, they all have limited explanations of their methodologies to obtain data. It is therefore difficult to assess the reliability of presented results and the applicability of the data in other studies. Several important recommendations made in the reports, such as the locations of the hydrological stations and the availability of hydrological and meteorological data for research, have not yet been implemented. The obtained reports were published between 2015 and 2020, thus the implementation could still be ongoing. In general, it was found that there have been few academic studies conducted in relation to catchment modelling and the hydrological impact of climate change in Rwanda.



Literature review

- Master plans and policy documents
- Hydrological studies in Rwanda
- HEC-HMS studies
- Missing data management

> Several recent governmental management studies and consultants design reports containing data relevant for hydrological modelling in Sebeya Catchment
> Few academic research studies performed in Rwanda with focus on floods, rainfall-runoff modelling, or catchment hydrology
> Few academic studies climate change impacts hydrology in Rwanda
> Several studies showed successful methods of statistically estimating missing data values

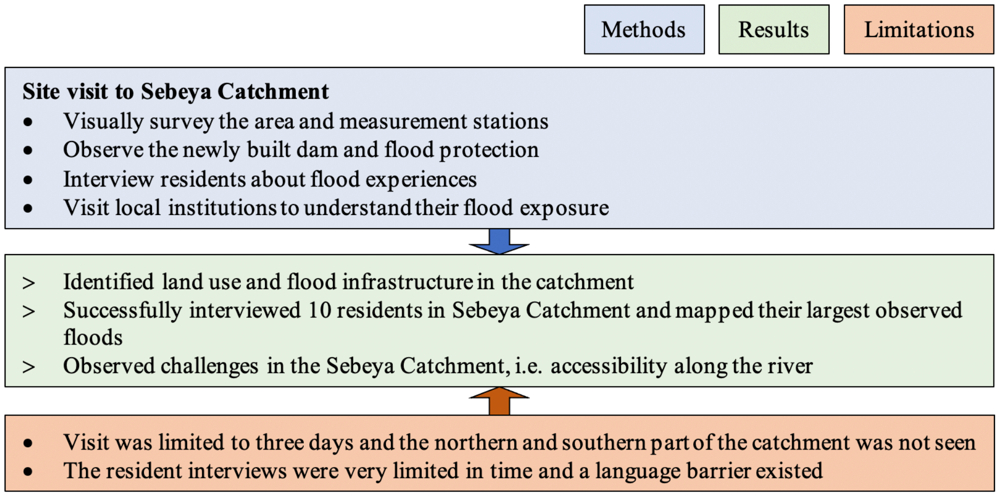
- Master plans and policy documents lack methodology sections and data references
- Studies based on the use of remote sensing data in hydrological modelling were not a part of the review

Figure 5-1 Results and limitations of the literature review.

HEC-HMS was found to be a popular model to use in data scarce areas, which justifies the use of the software to model Sebeya Catchment. This report did not specifically investigate the use of satellite data in hydrological modelling; however, HEC-HMS has the capability to use gridded data.

5.2. Sebeya Catchment Site Visit

It was made clear during the site visit that flooding in the Sebeya Catchment is an issue, although many inhabitants recounted that the situation has improved since the dike and retaining walls were constructed in Mahoko. Floods are rated as the least serious out of eight threats to the region in the Sebeya Catchment Management Plan (Ministry of Environment, 2018), which was written before the flood mitigating infrastructure was implemented. Mining activities are mentioned as the primary issue and this activity is suspected to affect the sediment load in Sebeya River. The build-up of sediment was observed to be a problem at the retention dike in Nyundo and sediment build-up was one of the causes of the severe flooding of the school Petit Seminaire Saint Piex de Nyundo. Soil erosion was another problem that was observed during the site visit and quoted as a threat in the Catchment Plan. Erosion of the riverbanks around hydrological measurement stations changes the river profile over time and affects the hydrological observations. In the past years terraces were constructed to delay runoff from the hills to the river and trees were planted to reduce soil erosion. These measures affect the land use and runoff characteristics of the catchment, which in turn affects hydrological models, especially continuous models run over a long period.



Site visit to Sebeya Catchment
- Visually survey the area and measurement stations
- Observe the newly built dam and flood protection
- Interview residents about flood experiences
- Visit local institutions to understand their flood exposure

\> Identified land use and flood infrastructure in the catchment
\> Successfully interviewed 10 residents in Sebeya Catchment and mapped their largest observed floods
\> Observed challenges in the Sebeya Catchment, i.e. accessibility along the river

- Visit was limited to three days and the northern and southern part of the catchment was not seen
- The resident interviews were very limited in time and a language barrier existed

Figure 5-2 Results and limitations of the site visit and interviews.

The site visit was limited by the allocated time. Therefore, it was not possible to visit the northern and southern parts of the catchment. The visit was also limited by the inaccessibility to some parts of the catchment. Some roads were not passable by car due to the condition of the road and especially the upstream part of the catchment do not have roads made for cars. This complicates any field studies due to access and affect the timing as the roads are in better condition during the dry periods.

The interviews gave a good indication of the problems of flooding in the area; however, the given information was sometimes contradictory. For example, most interviewees said that there had been no problems since the dike had been completed at Mahoko, which is contradicted by Interview 1 that experienced a flood in 2021. The interviewees were not always certain of the date or height of a flood. There is a possibility of there being misunderstandings regarding the date of the floods and what counts as a “flood event” versus normal rainy season problems. Many of the residents did not speak English which further increased the risk of misunderstandings as the interviews were conducted by the student assistants and not the author. It was difficult to find good reference points for the height measurements, the main roads at flat areas were found to be most reliable as the coordinates could be registered on Google Maps and imported into QGIS.

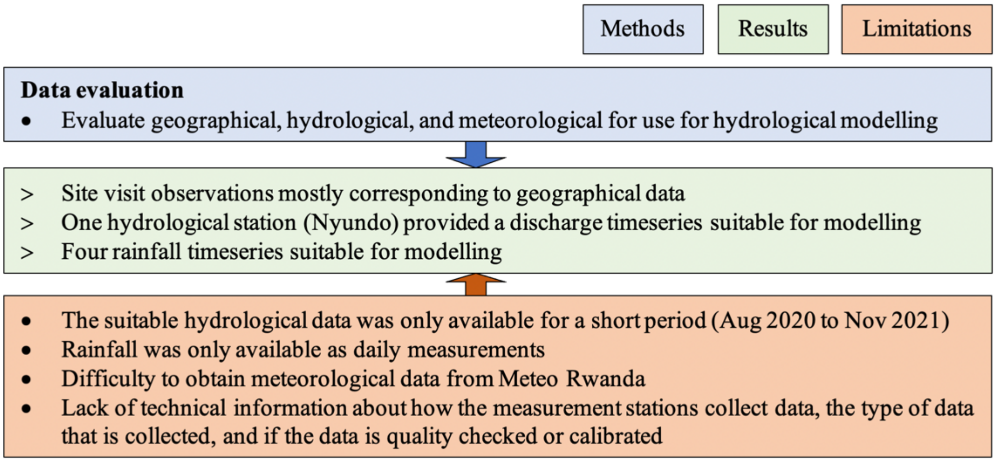
5.3. Data Evaluation

The geographical data were all recent (2018-2022) and compared well to the observations made during the site visit. This study was limited to not include the change in land use over time.

Data from hydrological measurement stations around Rwanda were available from the RWB’s WaterPortal, which was user-friendly. The main issue found with the hydrological data was that most of the stations in Sebeya Catchment only record stage and there were no reliable rating curves to convert stage to discharge, which is required for the HEC-HMS model. The telemetry data series were short and did not allow for a validation period in continuous models. There was also a lack of technical information about the telemetry stations, i.e. how they function and if data was calibrated for a change in the river profile. It should be noted that the trendline in the scatterplot of the telemetry stage and discharge from Nyundo station, Figure 4-12, did not intersect the origin (0,0).

No explanation could be found for why the Nyundo stage-discharge curve did not start at the origin as would be expected.

Two rainfall timeseries and one temperature timeseries were available from 1981 and 1983 respectively, which consisted of daily values and had no missing data. That no data should be missing appears unlikely given that the hydrological timeseries over the same period have several periods of missing data, however, no information was found about data quality checks by Meteo Rwanda. Seven other timeseries containing daily rainfall values were available starting from 2010 – these data sets had between 5 and 29 % of missing data. The analysis of the meteorological data was limited by not obtaining a full list of stations, with their coordinates, from Meteo Rwanda. It is not known if data from all stations in and surrounding the catchment were accessed. For example, the meteorological station observed in Nyundo during the site visit did not correspond to the coordinates of any meteorological station given by Meteo Rwanda. Due to the lack of technical information about the different types of meteorological stations in the catchment it was not possible to get an overview of what type of data that were available, i.e. rainfall, temperature, relative humidity, etc. This thesis did not investigate the availability and suitability of satellite data in Rwanda, however, the ENACTS (Enhancing National Climate Service) initiative combines bias corrected and reanalysed rainfall and temperature satellite data with station data (Siebert, et al., 2019). In Rwanda the spatial resolution is approximately 4 km and has a daily temporal resolution. The ENACTS initiative is done in collaboration with Meteo Rwanda and some of the received meteorological data may have been a result of this collaboration. The daily rainfall data works well for continuous rainfall-models, but event-modelling requires data of a higher resolution to capture a short, intense rainfall.



Data evaluation

- Evaluate geographical, hydrological, and meteorological for use for hydrological modelling

> Site visit observations mostly corresponding to geographical data
> One hydrological station (Nyundo) provided a discharge timeseries suitable for modelling
> Four rainfall timeseries suitable for modelling

- The suitable hydrological data was only available for a short period (Aug 2020 to Nov 2021)
- Rainfall was only available as daily measurements
- Difficulty to obtain meteorological data from Meteo Rwanda
- Lack of technical information about how the measurement stations collect data, the type of data that is collected, and if the data is quality checked or calibrated

Figure 5-3 Results and limitations of the data evaluation.

5.4. HEC-HMS Model

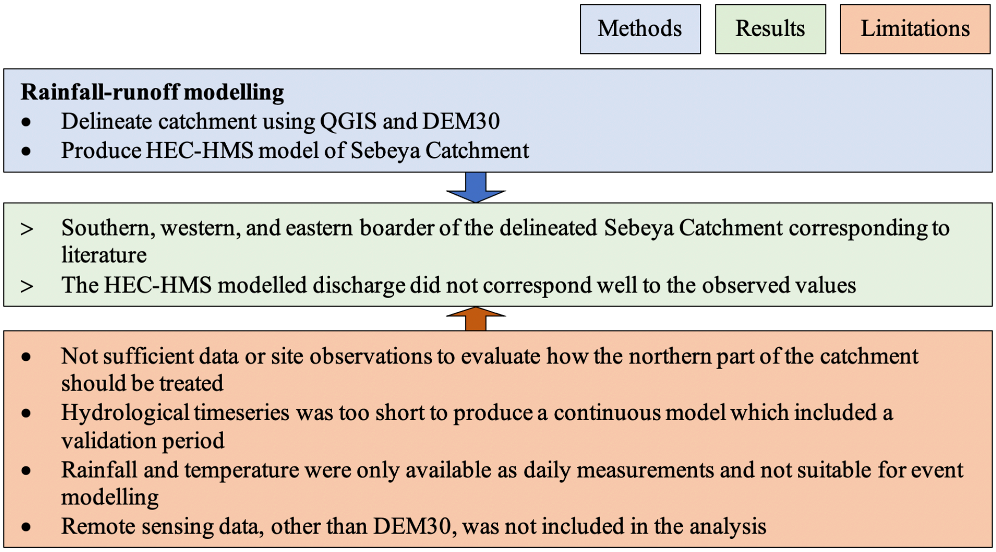
The delineation of Sebeya Catchment using QGIS and DEM30 was successful but showed a difference to other catchment delineations of Sebeya used in literature. It emphasises the need to investigate the hydrology and flow contributions of the northern part of the catchment. The catchment delineation was limited by the DEM file having a resolution of 30 metres. As the delineation is done over a large area (>300 km^2) with considerable height difference this is unlikely to have affected the result. A finer resolution would improve any flood analysis done in the flatter areas. A DEM with 10 metres resolution exists but has not yet been quality checked and contains errors. Topographical site surveys could be performed for more detailed flood modelling and mapping.

Only the area upstream of Nyundo was modelled as this area provided the only suitable data set. Modelling of the entire catchment was thus limited by the locations of the hydrological measurement stations and the lack of a telemetry station at Gisenyi. There is currently no station that considers the contributions of the northern part of the catchment and there is no station to cross-reference the combined flow of the Pfunda sub-catchment and upstream Nyundo (upstream Sebeya, Karambo and Bihongora sub-catchments).

As mentioned above, the hydrological data set was not suitable for continuous modelling as it was too short to allow for warm-up, run, and validation period.

Studies usually use several years of data for continuous rainfall-runoff models. Meanwhile, the meteorological data sets were not suitable for event-modelling as the resolution was too low with only daily measurements. This limited the HEC-HMS modelling of Sebeya Catchment, and it was not feasible to attempt to validate or calibrate the result of the continuous model. For event-based models, other methods of obtaining peak flows could be investigated, e.g. historical analysis, statistical analysis, or similarity analysis (BRL Ingénierie, 2020).

The modelling of Sebeya Catchment was also limited by the model approach chosen in this thesis. HEC-HMS is a software with various types of modes, and a common way to model ungauged catchments using HEC-HMS is to use the SCS-SN method which focuses on the soil characteristics in the catchment. However, it will not improve the possibility to validate the results due to the lack of hydrological data. This thesis did not evaluate the available geographical data for land use and soil properties and for the model the soil characteristics were obtained from literature, see Section 2.4.2.1.



Rainfall-runoff modelling
- Delineate catchment using QGIS and DEM30
- Produce HEC-HMS model of Sebeya Catchment

> Southern, western, and eastern boarder of the delineated Sebeya Catchment corresponding to literature
> The HEC-HMS modelled discharge did not correspond well to the observed values

- Not sufficient data or site observations to evaluate how the northern part of the catchment should be treated
- Hydrological timeseries was too short to produce a continuous model which included a validation period
- Rainfall and temperature were only available as daily measurements and not suitable for event modelling
- Remote sensing data, other than DEM30, was not included in the analysis

Figure 5-4 Results and limitations of the hydrological model.

6. Conclusion

The quality of the meteorological and hydrological data available for Sebeya Catchment was found to not be enough to successfully create a continuous rainfall-runoff model in HEC-HMS containing warm up, run and validation periods. The biggest hurdle was found to be the lack of continuous and long-term hydrological data series and the lack of rating curves for the daily stage data dating from 1974. The newly installed telemetry data stations have a potential to build up long-term data series but currently experience technical issues or missing equipment and thus contain data gaps. There is also no telemetry station installed at the river outlet at Gisenyi, and therefore no station captures the flow contributed by the entire catchment. The telemetry stations have a temporal resolution of 15 minutes which would be suitable for event modelling in HEC-HMS, however the rainfall and temperature data is only given as daily measurements by Meteo Rwanda. With no information about the daily hyetographs, it is not possible to model a storm event lasting a few hours to couple of days. Due to time limitations, this thesis did neither evaluate land use and soil characteristic geographical data nor test the SCS-SN model approach in HEC-HMS, which is a common way to model ungauged catchments.

The site visit was successful in providing an overview over the land use in the area, the flood protection measures that are in place, and the challenges in conducting visits to some of the more remote parts of the catchment. The interviews with local institutions provided insight into recent flood events, implemented flood measures, and reconstruction required due to floods. The interview with the residents gave an understanding of the extent the population is affected by floods. Eight out of ten respondents had experienced flooding or destruction of their homes or livelihoods due to floods, one respondent had also experienced the death of a neighbour because of a flood event. The large flood mitigating infrastructure that has been implemented – a dike at Mahoko and retaining walls in Nyundo and Mahoko – have according to the residents reduced the impact of average seasonal floods. It is however too early to say how they would perform in a major storm event.

6.1. Recommendations

6.1.1. Further Studies in the Sebeya Catchment

Recommendations

- Investigate the flow contribution of the northern area of the catchment
- Study hydrological role of the Gishwati Forest
- Investigate the sediment effect on the flood protection structures
- Produce a continuous rainfall-runoff model of Sebeya Catchment focusing on soil characteristics (SCS-CN approach)
- Investigate the availability of satellite or station meteorological data with higher temporal resolution suitable for event models
- Use residents´ experiences to validate the results of a flood map models in absence of flow data

Figure 6-1 Recommendations for further studies in Sebeya Catchment.

Several questions remain unanswered about the Sebeya Catchment. The northern area of the catchment was not included in the modelling work in this thesis. However, the basis for this approach should be further investigated, as the underground and non-perennial rivers can affect the flow the Sebeya River. If the rivers flow underground the areas would not have been included in the catchment delineation carried out in QGIS as this analysis is only based on the elevation of the area. The investigation could be inspired by the tracer method used in the studies done in the Migina catchment by Munyaneza et al. (2012). Furthermore, it should be considered to install a telemetry station at the river outlet in Gisenyi which would capture the flow of the entire catchment. It is important to understand the hydrology of the northern part of Sebeya Catchment to avoid new structures causing a blockage of the flows during heavy rains and in turn creating floods in new areas.

During the interviews around Sebeya, the Gishwati Forest was mentioned as a cause of flash floods. The geology or topology of the area was said to be retaining the water until a certain point where it is released and caused flash floods in the downstream Sebeya area. These claims could be investigated further. However, the problem may be solved by the dam currently being constructed upstream of the Karambo confluence (Water for Growth Rwanda, 2020b). The forest area and the area around Bihongora River are difficult to reach from the northern side but on maps appear more accessible from the southern side.

The effect of the high sediment load in the river was observed during the site visit to Sebeya Catchment. There was already a noticeable amount of deposited sediment around the inlet of the newly completed retention dike at Mahoko. Further investigation should be done on how the flood protection measures are affected by the sediment deposits. The sediment load is also a problem for the hydropower stations along the river.

HEC-HMS is a versatile software supporting different models used to model rainfall-runoff one of which is SCS-CN. This approach would require land use and geological maps and a long-term model would still not be validated due to missing long-term flow data. However, it is an approach that has been successfully used previous studies to model ungauged catchments. The interviews showed that in Nyundo and Mahoko residents have experienced floods of around one metre. These observations can be used to validate any future flood mapping studies where software such as HEC-RAS is used and there is a lack of historical data for calibration and validation. Especially older residents can provide important information regarding previous floods. Satellite rainfall and temperature data should be evaluated for the region – this data could be used in combination with the hydrological telemetry data to construct event models in HEC-HMS.

6.1.2. Data Resources for Hydrological Modelling in Rwanda

Recommendations

- Capacity building in database management within Meteo Rwanda and RWB
- Facilitate the access to meteorological and hydrological data in Rwanda
- Policy for accessing raw data collected by international consultants
- Initiate a programme to measure stage-discharge at selected locations
- Review the process of installing hydrological measurement stations
- Align governmental bodies and research institutions interest on hydrological modelling issues

Figure 6-2 Recommendations to improve data resources for hydrological modelling.

It was not possible to receive a list of all of Rwanda’s meteorological stations including names and coordinates despite several requests made to Meteo Rwanda. Thus, it was not possible to know if all stations were captured in the study area. It was only possible to request meteorological data based upon the name of a station, creating a Catch 22. The rainfall data was received as Excel files; thus, the data is likely stored in some type of database. Furthermore, when receiving meteorological data for a specific station the coordinates of that station are stated in the Excel file. Capacity building within data base management, data storage, and “big data” within Meteo Rwanda would improve accessibility to data used for research. The hydrological data (river flow measurements) is readily available for download through RWB’s website. For each dataset, such as stage measurements for a particular station, a data use questionnaire is required. For projects where only a few datasets are required this does not pose a problem. For projects requiring a large number of datasets this method of download is not feasible. Several of the policy documents and master plans discuss the importance of accessibility and availability to meteorological and hydrological data and proposes step to be taken, many of these steps are not yet implemented.

A general problem for the both the hydrological and meteorological data is that technical information is not available. Details of how the data are collected, which type of data that are available from which stations (primarily a meteorological station issue), if the data are checked or calibrated before being published would be useful in hydrological studies when evaluating the data.

Several studies have been conducted in Rwanda by international consultants, it is unclear if the raw data are available for research by the national agencies. The possibility to use and access this data, such as geotechnical investigations, should be investigated.

One of the main issues encountered during the rainfall-runoff modelling of Sebeya Catchment was the lack of stage-discharge data to construct rating curves. To address this, the RWB could establish a river flow data collection programme at selected hydrological stations in Rwanda. According to the HP Training Manual (DHV Consultants BV & DELFT HYDRAULICS, 1999) is a rating curve "established by making a number of concurrent observations of stage and discharge over a period of time covering the expected range of stages at the river gauging section". As there currently are problems with the telemetry stations, i.e. technical or missing equipment, the measurements could be done manually at the start.

It is important to consider the placement of new hydrological stations to ensure that the rating curves are consistent over time. During the site visit it was observed that some of the telemetry stations installed on Sebeya River did not adhere to the suggestion made in the Flood Mapping Report (BRL Ingénierie, 2020), particularly "cross section stability" and "absence of backwater effects". The newly built dams, retaining walls, and other hydrological structures could provide a better option as location for hydrological stations as they can provide permanent cross sections (sediment deposit dependent) and thus reduces the effort to establish rating curves as opposed to section with shifting profiles (DHV Consultants BV & DELFT HYDRAULICS, 1999). River profiles changing over time due to sediment deposits or construction should be monitored and data users should be informed if any calibration is done to account for a change in the stage-discharge relationship.

A personal relationship between researcher and governmental agency improves the access to hydrological, meteorological, and geographical data and reports, both public and unpublished. It is important that access to data is unbiased and easily available to different researchers. If an agency´s hesitance to share data is caused by financial interest this should be clearly stated. Discussions could then be initiated between the universities and the agency regarding the use of data for research purposes. Alternatively, a clear pricing strategy could be implemented by the agency.

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Water for Growth Rwanda, 2020c. Flood mitigation and protection structures on Sebeya River - Gisunyu-Karambo Protection Wall - Phase 3 Detailed Design, s.l.: s.n.

Water for Growth Rwanda, 2020d. Flood mitigation and protection structures on Sebeya River - Bukeri Diversion Channels - Phase 3 Detailed Design, s.l.: s.n.

Appendix

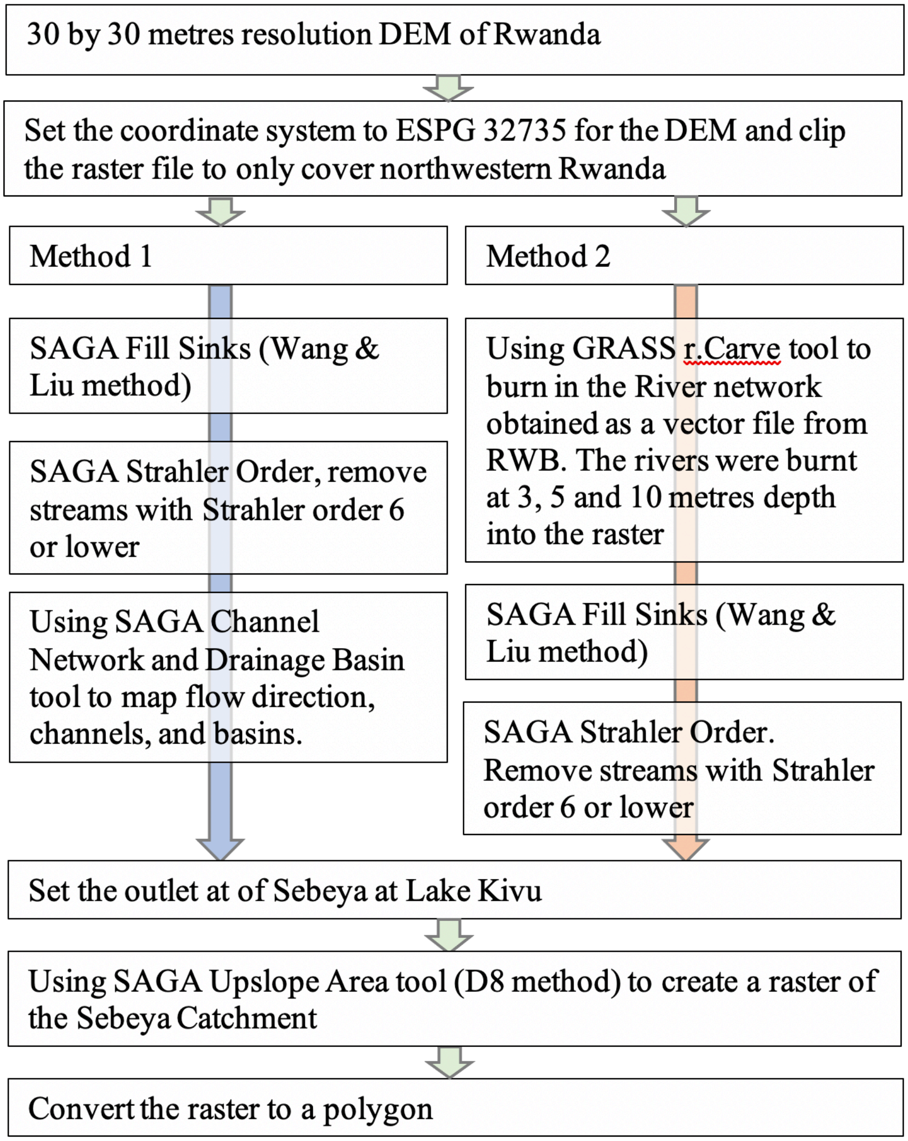
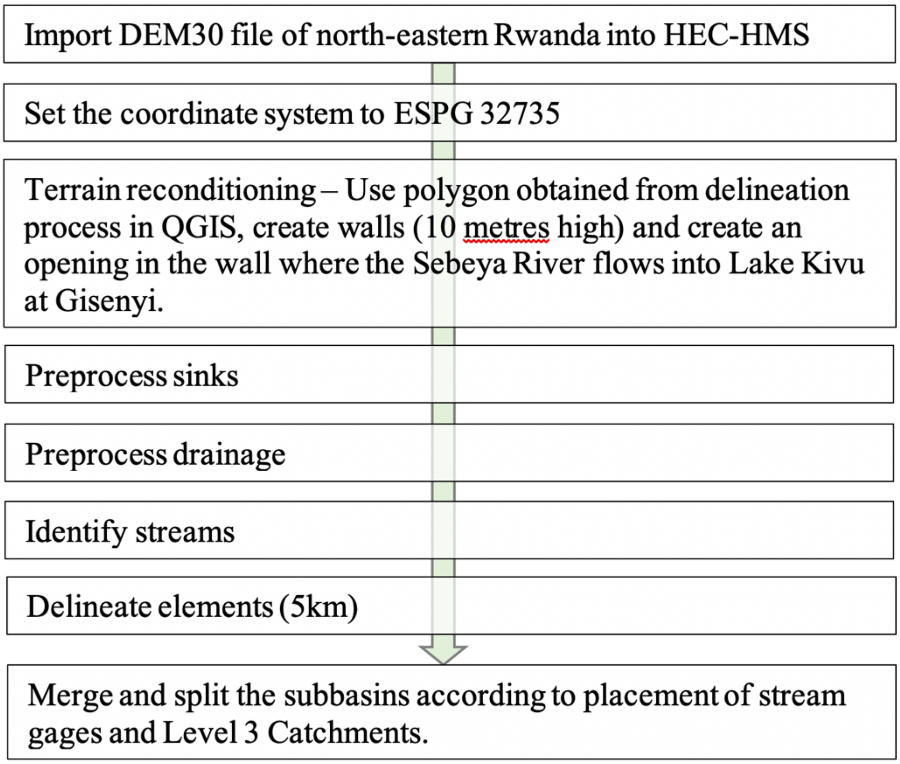


Figure A-1 Catchment delineation process in QGIS.



Import DEM30 file of north-eastern Rwanda into HEC-HMS

Set the coordinate system to ESPG 32735

Terrain reconditioning – Use polygon obtained from delineation process in QGIS, create walls (10 metres high) and create an opening in the wall where the Sebeya River flows into Lake Kivu at Gisenyi.

Preprocess sinks

Preprocess drainage

Identify streams

Delineate elements (5km)

Merge and split the subbasins according to placement of stream gages and Level 3 Catchments.

Figure A-2 HEC-HMS basin model element identification.

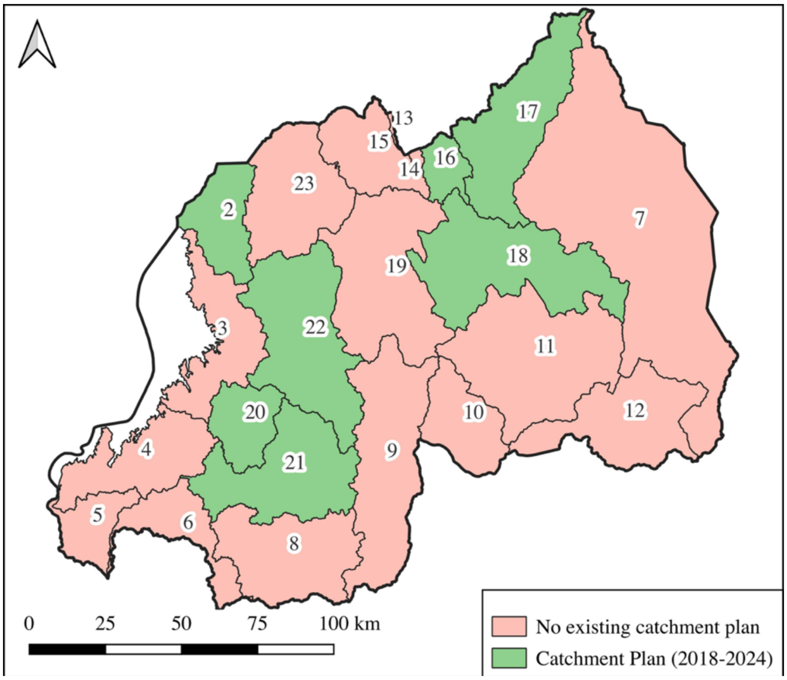


Figure A-3 Level 2 catchments with and without existing catchment plans.

Table A-1 Level 2 catchments with and without existing catchment plans.

Catchment Plan (2018-2024)			**No existing catchment plan**		
No.	*Catchment name*	*RWB ID*	*No.*	*Catchment name*	*RWB ID*
2	Sebeya (extended)	CKIV_1	3	Koko/Muregeya	CKIV_2
16	Muvumba (Murindi)	NMUV_1	4	Kamiranzovu	CKIV_3
17	Muvumba (Warufu)	NMUV_2	5	Rubyiro	CRUS_1
18	Nyabugogo	NNYL_1	6	Ruhwa	CRUS_2
20	Upper Nyabarongo (Mbirurume)	NNYU_1	7	Giswi/Agatobwe	NAKL_1
21	Upper Nyabarongo (Mwogo)	NNYU_2	8	Lower Akagera	NAKN_1
22	Upper Nyabarongo	NNYU_3	9	Gishara/Mukunguri	NAKN_2
			10	Cyohoha	NAKN_3
			11	Mugesera/Sake	NAKU_1
			12	Rweru	NAKU_2
			13	Upper Kiruruma	NKIR_1
			14	Lower Kiruruma	NKIR_2
			15	Burera/Ruhondo	NMUK_1
			19	Mambu/Base	NNYL_2
			23	Giciye/Mukungwa	NMUK_2

(MINIRENA-RNRA, 2015)

Figure A-4 Karambo station and river profile.

Figure A-5 Karambo retaining wall, downstream Karambo station.

Figure A-6 Bihongora station, river profile, and mining activity.
In the photo grey ellipses are used for anonymisation.