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Floods and landslides in the Bakokwe catchment, Rwanda

Causes, consequences, and future challenges

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Department of Building and Environmental Technology

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Abstract

Rwanda is highly exposed to floods and landslides due to intense precipitation, rapid population growth, varied topography and agricultural growth. One of the most vulnerable areas is the Nyabarongo catchment. A subcatchment of the Nyabarongo catchment, Bakokwe, was chosen as a case study for this thesis. The aim was to evaluate the causes, consequences and future challenges of floods and landslides in the subcatchment. This was done by evaluating soil profiles, reported disaster events, changes in land cover, and precipitation, and observations from the field visits. The causes of floods and landslides in the catchment could be concluded to be heavy rainfall together with land use and high population density. It could also be concluded that disaster events likely are being underreported, as the precipitation leading up to the reported events mostly was normal. The vulnerability to floods and landslides in the area is predicted to increase due to the alterations in the hydrological cycle that follows with climate change, together with a projected high population increase. This thesis suggests further research to be conducted, as the lack of data has been a limiting factor. It will be of importance that the governmentally proposed measures are implemented and regularly evaluated.

Sammanfattning

Rwanda har utsatts för översvämningar och jordskred till följd av dess intensiva nederbörd, snabba populationsökning, varierande topografi och expanderande jordbruk. Ett av de mest utsatta områdena är Nyabarongofloden och dess avrinningsområde, med delavrinningsområdet Bakokwe som valdes som fallstudieområde för detta arbete. Syftet var att undersöka orsakerna, konsekvenserna och de framtida utmaningarna med översvämningar och jordskred i delavrinningsområdet. Det gjordes genom att analysera regndata, jordprofiler, inrapporterade katastrofer, förändringar i landanvändning, och genom observationer från fältstudier. Orsakerna till översvämningar och jordskred fastslogs vara intensiv och kraftig nederbörd, i kombination med landanvändning och landets höga populationsdensitet. Katastrofer kunde också konstateras vara underrapporterade, eftersom nederbörden vid de inrapporterade katastroferna inte avvek från normala regn under samma tidsperiod. Utsattheten för översvämningar och jordskred i området tros öka med förändringar i det hydrologiska kretsloppet, till följd av klimatförändringarna, i kombination med den förväntade höga populationsökningen. Detta arbete föreslår att mer forsknings utförs, då bristande datatillgänglighet har varit en begränsande faktor. Det är av stor vikt att att de åtgärder som myndigheter föreslagit genomförs och utvärderas regelbundet.

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Introduction

Natural hazards, such as floods, are prominent problems in Rwanda due to its hilly landscape, tropical climate, agricultural livelihoods, vulnerable communities, and rapid population growth. Over the last decade, the intensity and frequency of these natural hazard events have increased and had severe consequences (Ministry In charge of Emergency Management [MINEMA], 2017-2022). MINEMA (MINEMAb, 2018) states that it is not only the natural hazards themselves that are causing diastral consequences, but rather the exposed and vulnerable community and population. The population density of Rwanda is considered one of the highest in Africa and the country had a total population of approximately 13 million in 2020 (The World Bank Group, 2022) with an average population density of 493 people/km^2 (MINEMAb, 2018). More than 80% of the population earn their livelihood from agricultural practices (Mikova et al., 2015) and the crop production meets 90% of the national food needs and generates more than 70% of the country's export revenues (Siebert et al., 2019). About 30% of the country’s GDP came from agriculture in 2015 (Rwandan Ministry of Finance and Economic Planning [MINECOFIN], 2015; Siebert et al., 2019). The government of Rwanda has acknowledged floods and landslides as one of the largest threats to agricultural production and hence a direct threat to food security and socioeconomic development of the country (Nsengiyumva, 2012; Rwanda Land Management and Use Authority [RLMUA], 2020).

In Rwanda, unsustainable and uncontrolled land use practices have led to increasing occurrence of and risk for soil erosion and floods. These tendencies have been significant in the south and west provinces, where a catchment named Nyabarongo is located (Karamage et al., 2016). Mind’je et al. (2019) performed a flood risk assessment of Rwanda and their results show that it mainly is the upper part of the Nyabarongo catchment and the southern parts of the lower Nyabarongo catchment that is most susceptible to floods. Nahayo et al. (2019) produced similar results, indicating that the entire southern province of Rwanda has a high vulnerability to floods. Within the Nyabarongo catchment, a subcatchment named Bakokwe and its river was identified as a case study area for this thesis. As the subcatchment contains few meteorological stations and rain gauges, it serves as a representative for a majority of the smaller subcatchments in Rwanda. It is also well located in terms of accessibility and extent.

Aim and research questions

The aim of this thesis was to identify the causes, consequences, and future challenges of flood and landslide events in the Bakokwe catchment. The following main research questions were used:

- What is the history of occurrence and impacts of heavy rainfalls, floods and landslides in the Bakokwe catchment?
- What have caused the changes to the occurrence and impacts of heavy rainfalls, floods and landslides over time?
- What outlooks can be identified on future floods and landslides occurrence and impacts?
    - What is the role of population growth in these outlooks?
    - What is the role of land use and livelihoods in these outlooks?
    - What is the role of climate change in these outlooks?

Background

Geography, topography and climate

Rwanda is located in East Africa and is landlocked by Uganda, Burundi, the Democratic Republic of Congo and Tanzania. Water bodies cover about 3% of the country's total area, with both lakes, rivers and streams. The climate of Rwanda is tropical, as it is located between one to two degrees south of the equator, which gives rise to rainy and dry periods. There are two distinct wet seasons which together contribute more than 70% of the annual rainfall. The first rain period extends from March to May and gives more than 40% of the annual rainfall. The second one spans between September and December, gives about 30% of annual rainfall (Siebert et al., 2019). As the climate is changing, the world faces an intensification of extreme precipitation patterns, both in terms of rain intensity, duration, and frequency (Houghton, 2015). In the tropical regions of Africa, the frequency of extreme weather events is predicted to increase significantly (IPCCb, 2022). Rwanda is mountainous and hilly, with a high variability in altitude, averaging at 1700 meters above sea level (masl) and its topography is illustrated in Figure 1.

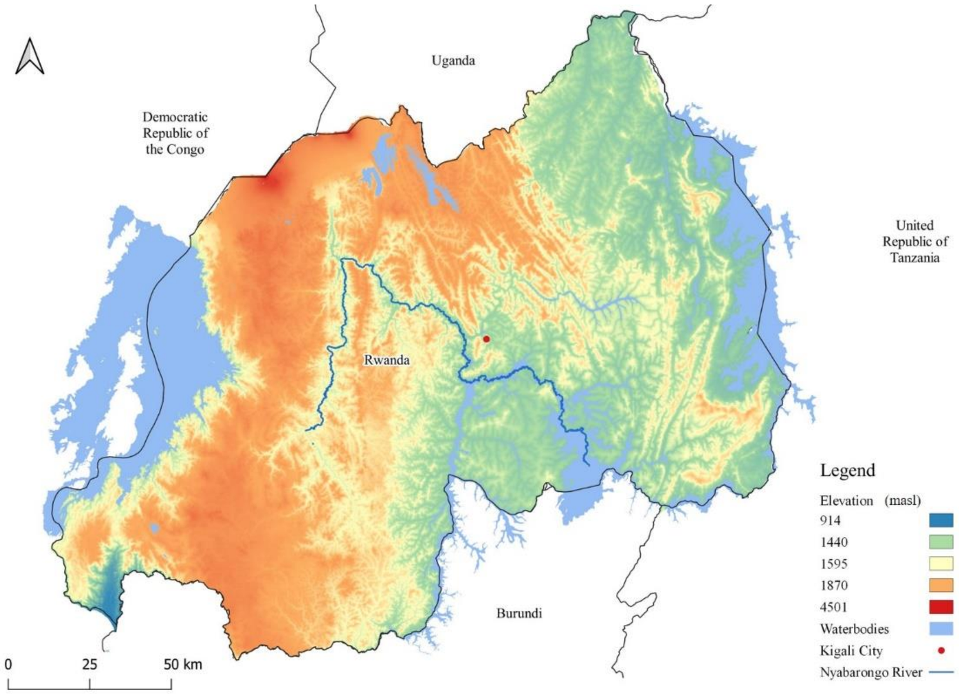


Figure 1. Topography of Rwanda. Dark red indicates the highest elevation in meters above mean sea level and the dark blue the lowest elevation.

In the central plateau of the country, the hills are undulating with elevations between 1500 and 2100 meters, whereas in the east the landscape is relatively flat with elevations around 1500 meters, which can be seen in Figure 1. The elevation is highest in the west part of the country, especially in the north western parts where there are volcanic mountains with the country's highest elevation at 4507 meters. In the southwest, the lowest lying land is situated in the tectonic depression of the East African Rift with an altitude of 900 meters above sea level (MIDIMAR, 2015). The precipitation patterns throughout the country vary a lot as the topography changes, with wetter patterns in the west compared to the east which mirrors the respective areas' susceptibility to floods. This together with the hilly topography of the west, the agricultural practices in the steep slopes of the north and large areas with deforestation of the south of Rwanda makes these parts of the country highly susceptible to floods. In contrast, the eastern parts have a low susceptibility. (Mind'je et al., 2019).

Floods, erosion and landslides

Floods are defined as an extreme surface flow where normal water levels are exceeded in an area with defined vulnerable resources that can be negatively affected. They are naturally occurring events and part of the hydrological cycle within a catchment and have beneficial and decisive influence on ecosystems as feeders of water in areas prone to floods, such as marshes and wetlands (Hamill, 2011; RLMUA, 2020). There are several meteorological drivers behind floods, mainly precipitation events with high intensity and long duration. The hydrological processes involved in events of floods also depend on catchment characteristics, such as elevation and land cover, geomorphology, and geology. Infiltration and storage capacity in the catchment, which depend on soil, vegetation types, and land use and land cover are other natural aspects that are affecting to what extent an area is flooded (Hamill, 2011). Floods can be further categorised into flash floods and riverine floods.

Floods with a large volume of water during a short period of time are called flash floods. Generally, a flash flood occurs because of a cloudburst, over a small drainage area, which most often is developed quickly. These types of floods result in flows reaching the maximum discharge fast, and then decreasing fast again. The flood wave of a flash flood often brings large amounts of sediment and debris and can result in destruction of infrastructure, buildings and public safety. Areas with deforestation, steep slopes or dry soil are especially susceptible. (Union of International Associations [UIA], 2019). Precipitation over large areas, and often with long duration, may on the other hand result in riverine flooding. Catchments with subcatchments that drain large areas are generally more affected than smaller systems. Factors that influence the flooding of a river are primarily the intensity, duration, amount and distribution of the rain and secondly the conditions of the ground such as the soil moisture, imperviousness and the vegetation surrounding the river. The flood wave is affected by when and how tributaries enter the river, the amount of temporary storage in the river and changes in the channel. Riverine flooding has had severe consequences throughout the world, especially when natural floodplains and buffering vegetation have been removed. (UIA, 2022)

Floods have been identified as the most recurrent natural disaster in Rwanda (Mind'je et al., 2019). As the country is considered as one of the most ecologically sensitive countries in Africa (Kulimushi et al., 2021) and floods affect the vegetation, soil structures and water quality (Ingabire et al., 2020), flooding is a big threat to the country. Floods may result in reduction in production of wetlands (Ingabire et al., 2020) and agricultural land (Mind'je et al., 2019), damages to infrastructure and buildings, injuries to people (MINEMA, 2021), erosion and possibly landslides (Kulimushi et al., 2021). Furthermore, floods tend to result in outbreaks of Malaria as more mosquitoes can thrive, as well as outbreaks of diarrhoea, cholera, and other viral infections (Mikova et al., 2015). At the same time, surplus floodwater during wet seasons are essential for surface and groundwater recharge. The annual probability of an inland flooding in Rwanda is above 20% (Asumadu-Sarkode et al., 2015). Between the years 1990 and 2015, 82 000 people in Rwanda were affected by floods of which 183 lost their lives (Asumadu-Sarkode et al., 2015), meaning a calculated average of 7 lost lives per year.

The risk of erosion is interlinked with the occurrence of floods since both increase the susceptibility of each other. Erosion is a geological process in which a natural force transports earth material away from its source. One of the most important factors behind erosion is water. Rainfall and runoff are able to scatter and transport sediment, and thus result in physical erosion. Erosion in turn causes higher amounts of floodwater downstream, which may result in additional soil erosion as the load of the soil and slope increases (National Geographic Society, 2018). Thus, erosion can both be regarded as a consequence and cause of floods. Erosion and soil loss further results in lowered water quality as the eroded material is contaminating the water, in lowered soil productivity as the topsoil is transported away (Kulimushi et al., 2021), and in severe damages to infrastructure (Nsengiyumva and Valentino, 2020).

Landslides are triggered by erosion. Landslides are a geological event where a mass of soil, rock or debris moves down a slope because the shear strength of the materials of the slope is exceeded. This can occur due to different reasons, for example because the base of the slope becomes too steep as a consequence of erosion or excavation. Furthermore, the shear stress can also increase by loading of the slope by rising water table, inflow of water, or heavy load on top of the slope. (Meng, 2022). Landslides can also be triggered by land use practices, deforestation, and cultivation on unstable hills or steep slopes (Nsengiyumva and Valentino, 2020).

National management plans

The government of Rwanda has identified these issues as threatening to the country and have developed national and regional plans to limit the impacts of natural hazards, such as heavy rainfall events, floods and landslides. This has been addressed through several policies and programs over the past decades. Between the years of 1997 and 2000, the strategy named Vision 2020 was founded by the Government of Rwanda and The Ministry of Finance and Economic Planning (MINECOFIN). The vision aimed for better livelihood for all people living in Rwanda where one of the key issues was “Natural resources, environment and climate change”, which mentioned flooding, deforestation, and droughts as major challenges (MINECOFIN, 2012). It acknowledged different areas of importance for development and change, and pointed out agriculture as one of the key features for the country’s socioeconomic development.

The Vision 2020 was followed by the more ambitious and long-term strategy Vision 2050. It projects that the population is expected to reach 22.1 million by 2050, a growth of 100% from 2020, and expects agriculture to have a decisive role in reduction of poverty and food insecurity, as well as increasing the socioeconomic standard (MINECOFIN, 2020). As part of Vision 2050, the comprehensive National Land Use and Development Master Plan (NLUDMP) was created in 2020 by Rwanda Land Management and Use Authority (RLMUA), which presents a way forward to meet the demands of food production while using the land sustainably. Agricultural land was recognized as the main land cover followed by forests, for which the preservation of good and useful land was stated as crucial. The NLUDMP (RLMUA, 2020) highlights deforestation as a threat, as the demand for firewood increases, and clarifies the vital role of forests as both life-supporting and with ecological benefits, but also for the protection of water bodies and the support of agricultural land. The plan further describes the challenges of the country's mountainous and hilly terrain, as these areas suffer from erosion, sediment transport, and storm water runoff (RLMUA 2020). The following water management related measures are presented in the plan to strengthen the climate-resilient options for conservation and development of land (RLMUA, 2020):

- Developing hydraulic and hydrological strategies supported by models in each district and catchment.
- Improving monitoring of rainfall, river flow, and groundwater.
- Developing water drainage and storm water management in more urban areas.
- Further expanding and developing floodplain zones in areas prone to floods.
- Provision of flood storage in environmentally sensitive areas.
- Increasing the extent of terraces plantations in hilly areas.
- Further conserving natural forests and developing agroforestry.

The measures presented in the NLUDMP (RLMUA, 2020) are supported by the suggested actions from Rwanda Water Resource Board (RWB) which has, in the context of Vision 2050, developed the Rwanda Water Board Strategic Plan, spanning from 2021 to 2030. One of the strategic objectives in the plan is “Strengthening resilience to flooding and landslides through improving preparedness, prevention, adaptation, mitigation, and response mechanism”, which is supported by concrete strategic actions to achieve the desired objective. Some of the presented actions are (RWB, 2021):

- Identifying high-risk zones for landslides and flooding.
- Enhancing data recording and information management systems and developing related databases.
- Collaborations between institutions to develop flood forecasting and early warning systems.
- Using remote sensing to provide improved predictions and real-time monitoring.
- To develop flood control infrastructures, such as dykes, dams, and hillside drainage systems.
- To use nature-based solutions to control floods and for the conservation of wetlands as retention basins.
- Apply climate change adaptation to planning and design of flood and storm water infrastructure.

One area that has been identified as an area with high risk of damaging flood and landslide events is the land that makes up the catchment of the Nyabarongo river (Mind'je et al., 2019) which covers the area chosen for the case study of this thesis.

The Nyabarongo catchment

The Nyabarongo river is a source of the Nile river and is the longest river in Rwanda with a total length of 351 km. Its catchment is draining approximately 33% of the surface of the country (Kulimushi et al., 2021) and in Figure 2, the river's path from west to east can be seen.

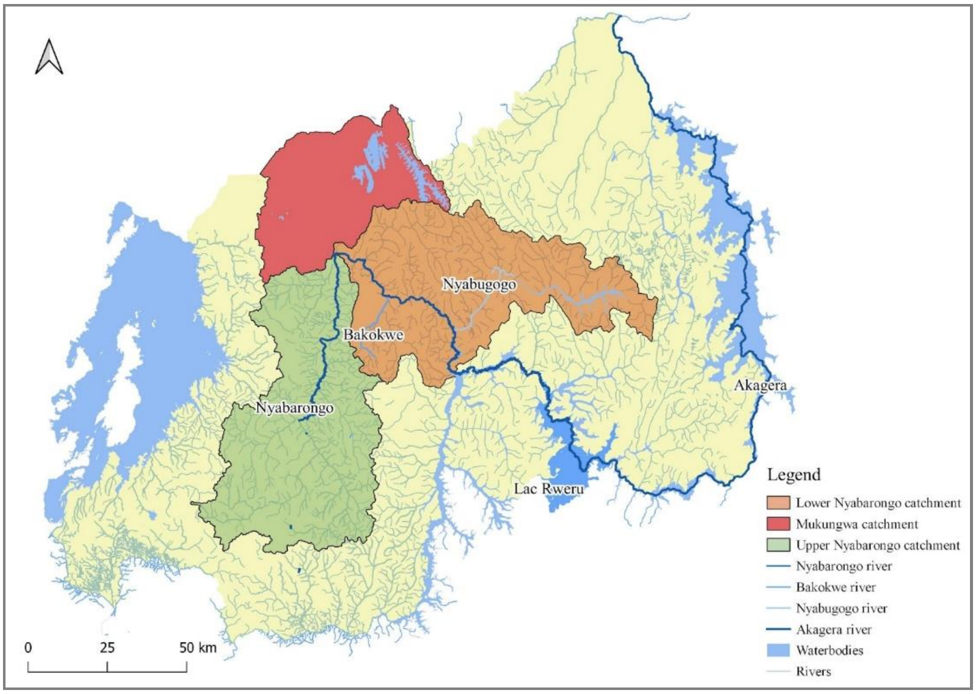


Figure 2. Rivers and waterbodies of Rwanda. The Upper and Lower Nyabarongo catchment is illustrated in green and orange, and the Mukungwa catchment is illustrated in red.

The Nyabarongo river originates from tributary rivers in the mountainous areas in the southwest and flows northeast before it turns south again, rounding the capital of Kigali where it merges with the tributary Nyabugogo, which drains the city of Kigali. It then continues towards Lake Rweru in the east, where it flows into the Akagera river that flows east and forms the border to Tanzania. The river eventually reaches Lake Victoria and then the Nile. The Nyabarongo river grows wider to the east where its extensive floodplains cover entire valleys (RWBb, 2022).

The Nyabarongo catchment is divided into a lower and upper part (see Figure 2). The upper Nyabarongo catchment is located in the southern part of the country, its surface area is approximately 3 350 km^2 and a significant portion of the catchment is characterised by high altitude and steep slopes with a large number of tributaries. The lower Nyabarongo catchment expands over an area of 3 300 km^2 and consists of many tributaries, one of them being the Bakokwe river. North of the Nyabarongo catchment is the Mukungwa catchment which drains into Nyabarongo river at the meeting point of the upper and lower Nyabarongo catchment. The Nyabarongo catchment is covered by 24 districts, presented in Figure 3, which in turn are divided into several sectors and villages.

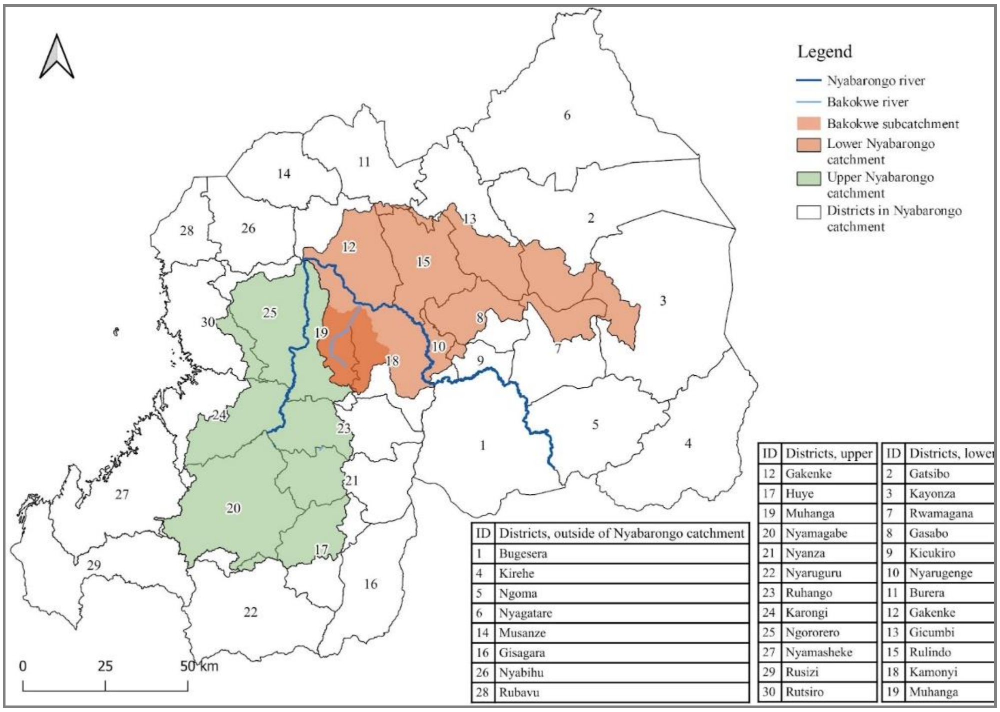


Figure 3. The 30 districts of Rwanda and the district covered by the upper and lower Nyabarongo catchment. The Bakokwe subcatchment is illustrated in dark orange.

Bakokwe catchment

The Bakokwe river catchment is located in the southern part of the lower Nyabarongo catchment. It has many smaller tributaries and flows north and merges with Kayumbu river before it enters the Nyabarongo river. The catchment is covered by the districts of Muhanga (19), which covers 55%, and Kamonyi (18), covering 45% of the total area, and it is surrounded by high hills on both sides. Bakokwe catchment is shared between 12 sectors and covers an area of about 377 km^2. Based on the population density of the sectors and the estimated covering area of each sector, a density of 493 inhabitants per km^2 can be estimated in the Bakokwe subcatchment (data from UNFPA, 2022), which is similar to the population density of the whole country (The World Bank Group, 2022). The average population density in Muhanga and Kamonyi districts is 544 inhabitants per km^2. Agriculture is the main livelihood for 82% of the inhabitants in Kamonyi district and 78% in Muhanga district (Kamonyi district, 2018; Muhanga district, 2018). Thus, about 80% of the population in Bakokwe subcatchment are most likely occupied by the agricultural sector. Since agriculture is the main livelihood sector in the area, regional plans have been developed to manage it.

Regional management plans

All districts of Rwanda are required to develop a District Development Strategy as a planning framework, with the goal to implement the National Strategy of Transformation (Muhanga district, 2018). The relevant parts of the District Development Strategies of Muhanga and Kamonyi are presented in the following sections.

Muhanga

In 2018, the district of Muhanga developed the Muhanga District Development Strategy 2018-2024, which presents the mission of becoming a green city with a focus on mining, quarry, and commercial businesses, though a total of eight objectives (Muhanga district, 2018). The objectives acknowledge degradation of the environment as an issue and mentions erosion, deforestation and human occupation as causes of degradation. In terms of agricultural production, the strategy mentions climate change, irregular growing seasons, and loss of biodiversity as some of the direct threats. The strategy identifies floods and erosion as possible disaster events for which residents should be relocated from high-risk zones. It mentions water harvesting techniques as action for erosion control, as well as measures for afforestation and terraces plantations, with a goal of a 100% increase in riverbank protection using joint erosion planning and agroforestry by 2024.

Aligned with the Muhanga District Development Strategy is the Muhanga District Land Use Plan (RLMUAb, 2021). The summary of the plan highlights mining, commercialisation, and urbanisation as its focus. It further states that transformation of the rural areas is key for social and economic development and that land consolidation will be promoted as a way of phasing out scattered farms and expanding commercial agricultural production and housing development.

Kamonyi

The corresponding District Development Strategy (2018) for Kamonyi district includes four objectives, one of them being to maximise production and productivity of agriculture and livestock (Kamonyi district, 2018). The strategy has acknowledged climate variability and seasonal fluctuations with floods and droughts as direct threats to agricultural productivity. The strategy has also identified a reduced consideration of climate change and environmental concerns among the population, destructive use of wetlands and water resources, deforestation and erosion as some of the issues that counteract the development of the district. The strategy mentions solutions such as making sure that the increase of agricultural productivity does not contribute to deforestation or soil degradation, and mentions land protection against soil erosion with an increase of progressive and radical terraces, increasing the construction of rainwater harvesting and increasing the forest cover.

The Kamonyi District Land Use Plan is aligned with the previously mentioned District Land Use Plan for Muhanga district. It identifies urban densification as a key strategy for efficient land management, and states that all the land outside urban areas and rural settlements should be reserved for non-residential activities such as agriculture, mining, or forestry (RLMUAa, 2021).

Methodology

Two main methods were used, one literature study and one case study. The literature study was conducted to obtain an overview of the current and historical situation of floods, landslides and heavy rainfall in both Bakokwe and Nyabarongo catchment. Furthermore, a case study of Bakokwe subcatchment was conducted which included gathering of online information and field measurements, followed by statistical and geographical analysis in Matlab and QGIS. As the flood situation of Bakokwe subcatchment has not been evaluated in previous studies, many of the features found on national level and in Nyabarongo catchment were used to make assumptions about Bakokwe. The main methodological components are illustrated in Figure 4, and are described in detail in the following sections.

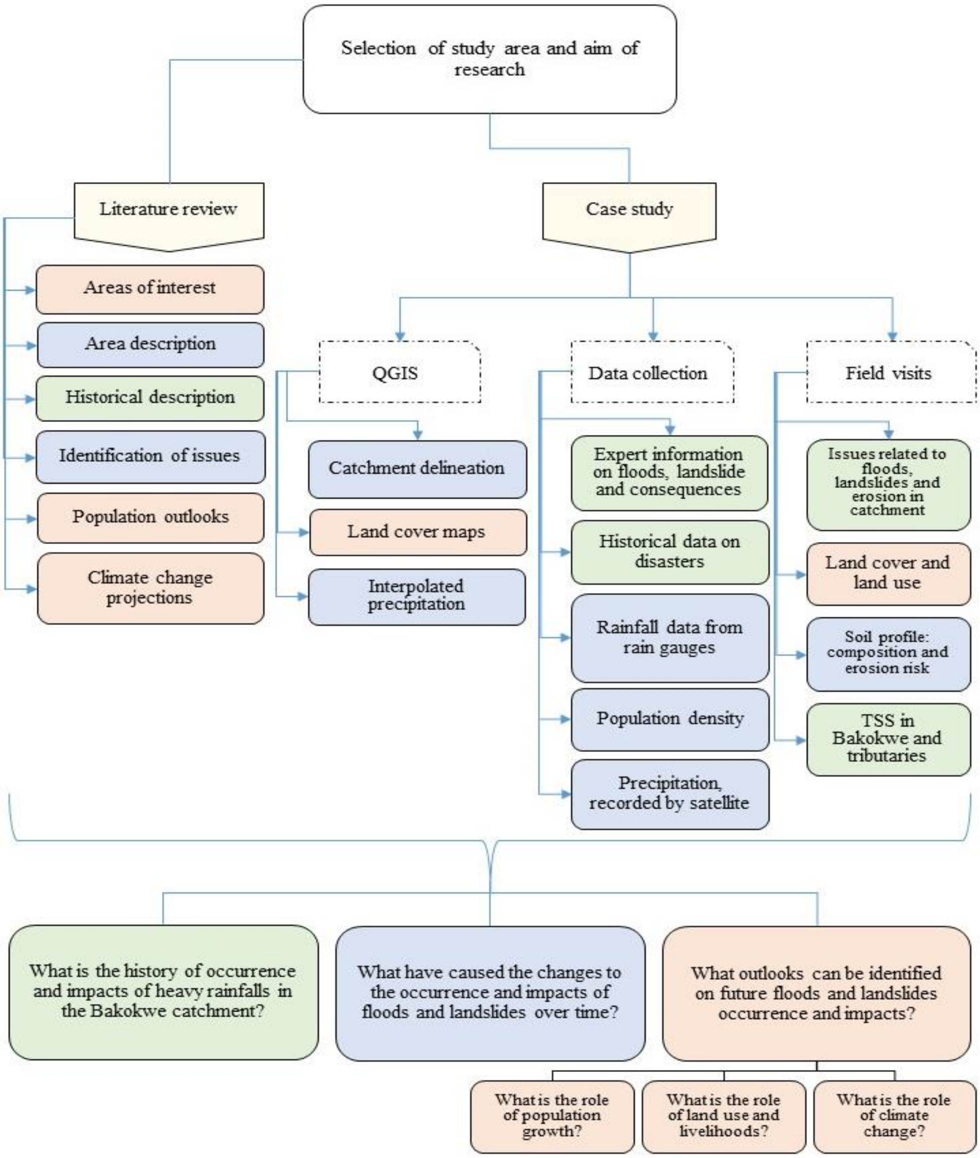


Figure 4. Flowchart of methodology. The different colours connect the research question with the main corresponding results. Some results were used to answer more than one question.

Literature review

A literature review was conducted by gathering reports from online databases and websites. The reports were then reviewed and selected for inclusion in the literature review if they dealt with any of the following topics:

- Flooding in the Bakokwe subcatchment or Nyabarongo catchment.
- Issues with flooding in southern, western, or northern provinces of Rwanda.
- Management of land use or flood prone areas.
- Land use or land cover in the Nyabarongo catchment or Rwanda.
- National or regional plans regarding land use, climate adaptation and management of floods, landslides, and erosion.
- Population density and development.
- Social and economic status in the Nyabarongo catchment or Rwanda.

The reliability of the selected studies was examined and studies that had not been peer reviewed were excluded from the selection. Due to the limited amount of studies performed regarding the above presented topics, reports down to, and including, master thesis level have been included in the literature review.

Case study

The case study of the Bakokwe subcatchment was the most extensive part of the methodology and has been conducted in several smaller parts. Each part is described in separate sections, presented in chronological order as conducted.

Describing the Nyabarongo and Bakokwe catchments

To decide where to perform field investigations, the area of interest had to be described and explored. This was done with the help of the literature review, google maps, and guidance from the local supervisor Assistant Lecturer Mr. Leonard Nzabonantuma at University of Rwanda, for data collection. The Bakokwe subcatchment was chosen based on recommendation from Leonard Nzabonantuma, whose perception was that Bakokwe is representative of many subcatchments in the Nyabarongo catchment, as well being logistically convenient to reach from Kigali.

The subcatchment's geological and geomorphological characteristics were determined with the Soil Atlas of Africa constructed by the European Soil Data Centre in 2013 and by a digital elevation model (DEM) with resolution of 30 times 30 metres from 2015. The subcatchment was delineated with the software QGIS Hannover 3.16 and the 30x30 metre DEM model by locating the outflow of Bakokwe river into the Nyabarongo river. A flow chart of this procedure is presented in Appendix A.1.1, together with the metadata of the files used. According to statistics from the United Nations Population Fund (UNFPA), the most recent population census was from 2012, which was used to calculate and estimate the population density for Bakokwe catchment in 2020 (HDX, 2022).

Data collection

Data needed for the case study was gathered from different sources, the methodology used to retrieve the data are presented in separate sections.

Questionnaires

A questionnaire was created and distributed to the Rwanda Water Resource Board (RWB), Rwandan Land Management and Use Authority (RLMUA), Rwanda Ministry in Charge of Emergency Management (MINEMA) and the two district offices sharing the subcatchment of Bakokwe - Kamonyi and

Muhanga. The goal was to collect expert information from the institutions and preferable from several individuals in each institution. The questionnaire contained 10 questions, where the six first questions were formulated to get text answers from the respondee on their expertise of flood events, management and improvement possibilities. In the last four questions the respondee was asked to rate the likeliness of different consequences of floods on a scale from 1 (not likely) to 6 (certain). The questionnaires were distributed through contact persons at each institution who in turn distributed the questionnaires to experts in flood- and storm water management as well as social and economic consequences of natural disasters. Physical meetings were held with the contact persons and they were provided with both soft and hard copies of the questionnaires. After one to two weeks, a reminder was sent out, and after three to four weeks, the answers of the questionnaires were collected. If no answers were provided before the 6th of May 2022, no more efforts of collecting the answers was made. The questionnaire and full answers are presented in Appendix A.3.1.

Rainfall data

The websites of RWB and Rwanda Meteorology Agency (METEO) were used to extract relevant information on location of meteorological stations, as well as data on rainfall in Nyabarongo and Bakokwe rivers. All available rainfall data from 1st of January 1980 till 31st of December 2019 from meteorological stations within the Nyabarongo catchment were retrieved from METEO by contacting the agency directly. Additional rainfall data was retrieved for 1st of January 2020 till 31st of December 2021 for the stations located in the near Bakokwe area. No data was available for the months of 2022 from the meteorological stations at the time of data collection.

Satellite rainfall data

Rainfall data for the last year, January 2021 to May 2022, covering an area extending over the Nyabarongo catchment between the coordinates (29.1E, 1.5S), (29.1E, 2.6S), (30.6E, 1.5S) and (30.6E, 2.6S) were collected from the dataset African Rainfall Climatology, version 2 (ARC2). This database was created by National Oceanic and Atmospheric Administration (NOAA), National Centres for Environmental Prediction (NCEP), Climate Prediction Centre (CPC), and the Famine Early Warning Systems Network (FEWS). The dataset has a spatial resolution of 0.1°, centred over Africa and is a long-term daily precipitation estimation dataset based on satellite imagery, with historical data dating back to the first of January 1983 (Novella and Thiaw, 2013). The retrieved satellite data was validated by performing a regression analysis on the data gathered from the rain gauges for the period January 1983 to December 2021 and by the data from ARC2 covering that same time period. In order to enable the regression analysis, the daily precipitation from the ARC2 database had to be interpolated linearly over the Nyabarongo catchment and the resultant values on the locations of the rain gauges extracted. These values could then be used for the regression analysis in Matlab, which was performed on the average values for every 14-day period. Then the R^2-values were evaluated.

Flood data

Data on flood, landslide and heavy rainfall events in the Nyabarongo basin were gathered from MINEMA through their website and from personal contact with Mr. Alphonse Hishamunda, Ag. Director of Prevention and Mitigation Unit at MINEMA, on causes and consequences of annual reported disasters. Meetings were also arranged with employees at MINEMA to access more detailed information on time, duration and location of effects of natural disasters. MINEMA have published annual reports covering 2016-2020 on the effects of natural disasters in Rwanda, including consequences of floods, landslides, and heavy rainstorms, as well as earthquake, fire, hailstorm, lightning, mine disaster, and windstorm (MINEMA, 2021). The reported disaster consequences are categorised into the following categories: loss of human lives, human injuries, loss of crop area, damage to property, damage to roads, damage to bridges, loss of livestock, damage to classrooms, and damage to health centres, damage to churches, damage to administrative offices, damage to water supply, and damage to transmission lines. The causes and consequences of disaster events were reported by the affected sectors and the data was compiled by MINEMA into annual reports (Hishamunda, 2022). The yet not published report from 2021 was gathered from personal contact with Alphonse Hishamunda.

Relevant reports on humanitarian efforts by the International Committee of the Red Cross (ICRC) in Rwanda concerning floods, landslides and heavy rainfall were gathered. In addition, the ICRC was contacted to access information on how they distributed their efforts and monitored floods that were not yet published. Information from the Famine Early Warning Systems Network (FEWS NET) was also gathered for extreme rainfall events resulting in flood issues in Rwanda.

News on floods, landslides, and heavy rainfall events in Rwanda were retrieved from the Rwandan English language newspaper New Times, from BBC, and reports from the UN-founded independent newsroom, the New Humanitarian. The news and reports gathered were from the last 12 years, 2010-2022, and contained reports of consequences such as damages, injuries and lost lives.

Furthermore, to provide validation of flood exposure following rain events in the Bakokwe River, an inhabitant living close to the river in one of the selected observation locations was hired to provide pictures and videos of that location after and during heavy or intense rainfall between 16th of February and 16th of April. This was done as a compliment due to lacking flow data in the area. These recordings were made without any risks to personal security.

Land cover and land use data

The website of the RLMUA was used to download data on the land cover and land use (LCLU) of the area. However, their data on land cover and land use was not publicly accessible in shape- or raster files which were needed to process it with QGIS. Thus, RLMUA was contacted directly to request access to recent land cover maps of the area. They had not completed the analysis of Rwanda after 2019 but provided guidance on using the ESRI Land cover mapping from 2017 to 2021. ESRI derived the global LCLU maps from Sentinel-2 imagery with the resolution 10x10 metres for each year by using a training dataset of billions of human-labelled pixels, which were developed by the National Geographic Society. The analysis of LCLU of Bakokwe subcatchment was made on 10 separate classes, which are presented in Table 1. The year 2017 may have less accurate land cover due to it being processed from a smaller set of images than the other years (ESRI, 2022).

Table 1. Land cover classification used by ESRI (2022).

Class	**Description**
Water	Water is predominantly present throughout the year. Little to no vegetation and no rock outcrop. Examples: rivers, ponds, lakes.
Trees	Any significant cluster of tall and dense vegetation. Generally closed or dense canopy. Examples: wooded vegetation, plantations, mangroves.
Flooded vegetation	Any type of vegetation with obvious mixing of water throughout the largest part of the year. Examples: flooded mangroves, rice paddies, wetlands, heavily irrigated agriculture.

Crops	Human planted crops, grasses and cereals which are lower than tree height. Examples: corn, wheat, fallow plots of structured land.
Built area	Structures created by humans. Examples: houses, dense villages, towns, cities, paved roads, asphalt.
Bare ground	Areas of soil or rock, sparse to no vegetation throughout the year. Examples: exposed soil or rock, deserts, sand dunes, mines.
Snow/Ice	Permanent snow or ice in homogenous areas. Examples: glaciers, permanent snowpack, snow fields.
Clouds	Persistent cloud cover, thus no land cover information can be recorded.
Rangeland	Open land, covered in grass with no or sparse tall vegetation. Fields with no obvious human plotting. Examples: natural meadows and fields, open savanna, golf courses and lawns, parks, pastures. Also shrubs, short trees or other plants.

Historical information on land use and land cover was also retrieved from the Regional Center of Mapping of Resources and Development (RCMRD) for the available years 1990, 2000, 2010 and 2015 (Open Data Site RCMRD, 2022). The classification used by the RCMRD were based on six land cover classes; settlement, cropland, forestland, grassland, wetland and water bodies (RCMRD, 2015). The land cover classes from ESRI (2022) and RCMRD (2015) were merged in order for the data to be presented in a uniform way. The merging of classes was done according to Table 2.

Table 2. The names used for the merged classes are presented in the column furthest to the right, and which classes were considered the same in the two classifications are presented in the left and middle column.

ESRI (2022)	**RCMRD (2015)**	**Used names of classes**
Water	*Water Bodies*	Water
Trees	*Forestland*	Forest
Flooded vegetation	*Wetland*	Wetland
Crops	*Cropland*	Cropland
Built area & Bare ground	*Settlement*	Settlement
Rangeland	*Grassland*	Open land
Snow/Ice	-	Snow/Ice
Clouds	-	Clouds

OpenStreetMap data was collected to retrieve updated information on roads, water bodies, and cities. Information on administrative boundaries and livelihoods was retrieved from ROSEA (2021). Furthermore, the land cover in 2020 was also mapped with Landsat 8 imagery by creating 10-20 training samples for each land cover class. The training samples were created by analysing the imagery displayed with panchromatic and multispectral bands, normalised difference vegetation index (NDVI) bands and modified normalised difference water index (MNDWI) bands and bands displaying the texture features. The 26 different bands were used to enhance the precision of the analysis. With the help of the SCP-tool in QGIS Hannover 3.16, the training samples were used to classify the land cover in Bakokwe catchment for 2020. A flowchart of this procedure and all steps taken is presented in Appendix A.1.2, together with the metadata of the files used.

Field visits

The objective of the field investigations was to understand the characteristics of the field sites in Bakokwe subcatchment, to estimate the average discharge of Bakokwe river as the area lacks stations measuring discharge and to understand how floods occur and affect the area. The average discharge of Bakokwe was then compared with collected rainfall data recorded before the field visits in order to estimate a relationship between the discharge and rainfall to be used to estimate flood extent due to heavy rainfall. The locations of the field sites were chosen together with Mr. Nzabonantuma, and are presented in Figure 5. The field sites were either confluence points, points in rivers, bridges, or roads.

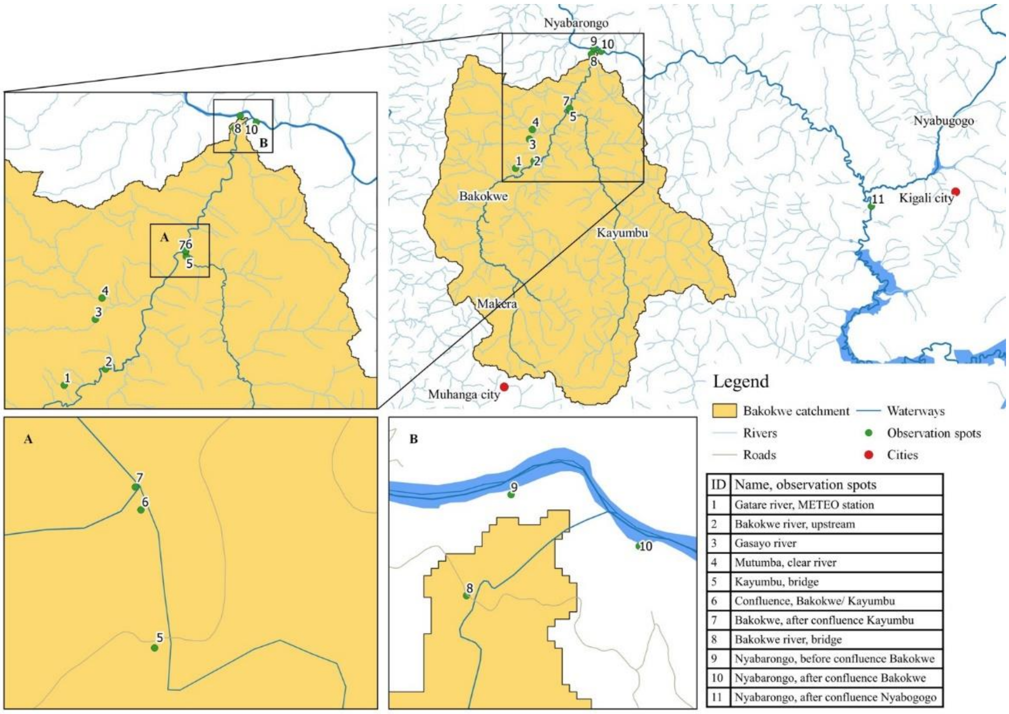


Figure 5. Maps of selected field sites in the Bakokwe subcatchment.

To understand flood exposure and flood risk due to heavy rainfall, the field sites shown in Figure 5 were chosen to investigate how the tributaries Gasayo, Kayumbu, and Makera contribute to Bakokwe River, how Bakokwe River contributes to the Nyabarongo River, and to see how the Bakokwe River and catchment characteristics change as the river progresses. During the field investigations, two bachelor students in Water Resource Management from the University of Rwanda joined and assisted in facilitating interviews with inhabitants, conducting measurements, and observing the characteristics of the catchment. At all locations, notes were made on the flood risk characteristics of the locations. All measurements taken are described in the following section.

Measurements

To estimate the discharge and velocity of the Bakokwe River, measurements of the depth, width, time, and length were taken at two locations, which were chosen based on the accessibility of the river. The measurements were taken in late February. The field investigations were conducted during three days, and are presented in Table 3.

Table 3. Date and day of visiting locations and what was done each day.

Day	**Date**	**Locations visited**	**Activities performed**
1	21-02-22	Locations 1, 2, 8 and 9	Measurements of velocity, width, length and depth. Description of site characteristics of surroundings.
2	22-02-22	Locations 5, 6, 7, 8 and 9	Determination of soil profiles. Validation of width measurements. Description of site characteristics of surroundings.
3	01-03-22	Locations 1, 3, 4, 5, 6, 7, 8, 9, 10 and 11.	Measurement of TSS. Description of site characteristics of surroundings.

The width was measured together with the depth at one-metre width intervals. Different types of floating objects (lime fruit, plastic water bottle with water, leaf) were then lowered into the river. These measurements were repeated three times in each location and an average time was used to approximate a velocity in accordance with the proposed procedure in the EN ISO 748:2021 standard (The European Committee for Standardisation [CEN], 2021). These measurements were then used to estimate the discharge, as described in the section named 'Calculation of discharge'.

To validate that erosion and sediment transport is an issue in the Bakokwe subcatchment, the total suspended solids (TSS) in Bakokwe, Gasoya, Kayumbu, and Nyabarongo rivers were measured in the beginning of March. These measurements were performed with the help of lab technician Mr. Mardochée Birori who provided the TSS-meter, water bottles for sampling and distilled water. The measurements were done by first collecting water at the sampling point, followed by calibrating the TSS-meter used with distilled water and then measuring the TSS in the sample. If the TSS were higher than 1000 mg/l the sample had to be diluted for the machine to work properly. The dilution was done with a pipette and distilled water.

Classifications

To ensure that the field visit team considered the same information when describing the land cover, a set of merged classes from RCMRD (2015) and ESRI (2022) were selected. The selected classes of land cover were Water, Forestland, Wetland, Cropland, Settlement and Open land. The geomorphology and geology impacts the erosion susceptibility and was thus considered interesting at the field visit. The area was classified according to the classification used by Kwisanga (2017), which were characterised by humic nitisols, ferrosols, high slopes, porous material, impermeable material, erosion and hills (RWBa, 2022).

Data processing

The collected data was processed in order to facilitate the analysis of it, this is presented in the following sections.

Calculation of discharge

The measurements from the field investigations of depth, width, time, and distance were used to calculate an approximate velocity and discharge. The velocity was calculated by dividing the measured distance with the measured time, and the cross section area of the three locations was calculated between the depth and the width of the measured points. The cross section was then used to calculate a median discharge at the point of measurement, with equation 1.

$$Q = 0.85 \cdot v \cdot A \qquad \text{Eq. 1}$$

Q = discharge in m^3/s,

v = velocity in m/s, and

A = calculated cross section area in m^2.

A term of 0.85 was introduced to account for the fact that the surface velocity is not representative of the velocity at all depths nor at all distances from shore (CEN, 2021). In order to estimate the travel time in the Bakokwe subcatchment, the measured discharge velocity of the Bakokwe river was used together with an approximated surface runoff velocity of 0.1 m/s. The distance from one end to the other of the catchment area was measured in QGIS and approximated to the furthest distance possible in order to make sure that as few events as possible were overseen.

Land cover

The land cover data were processed to portray changes in the Bakokwe catchment. First, the raster layers were cut to only convey the area of the Bakokwe catchment and the corresponding classes were given the same colours to convey comparable results. To get the percentage of each class for each of the analysed years, the zonal histogram tool in QGIS Hannover 3.16 was used to calculate the number of pixels of each class. The population density in each district of the Nyabarongo catchment was also computed and illustrated with the help of QGIS and the retrieved statistics from the UNFPA (2020).

Rainfall data

The number of operating meteorological stations with registered rainfall data was analysed to overview how the amount of available data differed between 1980 and 2019. A compilation of the number of stations with available data was therefore made for the lower and upper Nyabarongo catchment. If a station had registered rainfall data for 6 months or more for one year, it was considered an operating meteorological station.

Rainfall data were analysed to identify the total rainfall, intensity and duration of the periods of reported floods and landslides, and potential changes in rainfall patterns. All rainfall data prior to 1980 were excluded as the amount of available data and operating meteorological stations were limited. The data were then screened and investigated. In the cases of several sets of data for the same meteorological stations and dates, an average rainfall was computed for each date.

The rainfall data gathered from both METEO and the ARC2 database was normalised over the surface of the Nyabarongo catchment by computing the daily average and standard deviation of each location for each time period that had a subsequent reported event, and then calculating the normal daily mean precipitation for each location and time period according to equation 2.

$$N = \frac{X - \mu}{\sigma} \quad \text{Eq. 2}$$

N = the normal daily value, a factor of how many standard deviations the observed value deviates with,

X = the observed daily mean value over the time period,

μ = the historical daily mean value over the same period historically, and

σ = standard deviation over the historical time period.

The standard score for all locations was then interpolated in QGIS with the inverse distance weighting (IDW) method, assuming that two values that are closer to each other are more related than two further away from each other. The interpolation was done to the extent of the Nyabarongo catchment and then the area of interest was extracted from this interpolation. The area of interest corresponds to reported events of a flood or landslide, and the time of interest relates to the calculated travel time for the catchment. The resulting interpolation of the standard score was used to evaluate whether the rainfall leading up to the event was considered normal or not. The work process and all metadata used in the QGIS process is presented in Appendix A.1.3.

The raw reported rainfall data was also used to analyse rainfall intensities and durations for 2016-2021, where daily rainfall from both meteorological stations within the Bakokwe catchment was plotted against time and presented with estimations of disasters for the corresponding year. Potential rainfall patterns for the period of 1980-2020 in Bakokwe catchment were also analysed. For that analysis was an average reported daily rainfall calculated for the two meteorological stations located in the Bakokwe catchment, this to reduce the amount of data and present the result more clearly. The average daily rainfall was then used to calculate the total monthly rainfall and the results were plotted against time to evaluate potential historical climate variabilities in the area.

Flood data

The data retrieved from MINEMA and Mr. Hishamunda was sorted into categories on the basis of causes and consequences registered in Rwanda. Categories, with what was considered similar names or meanings, were viewed as one category and the categories of “damage to roads” and “damage to bridges” were summed to one. The reported annual disaster events by MINEMA in the Bakokwe districts, Muhanga and Kamonyi, were further analysed to identify the impacts of heavy rainfalls, floods and landslides in Bakokwe catchment. The reported disasters on district level did not distinguish floods, landslides, and rainstorm from other events and could therefore have been caused by any of the following events: earthquakes, fires, floods, hailstorms, landslides, lightning, mine disasters, heavy rainstorms, and windstorms. The different categories were then plotted in column and pie charts to overview the proportions of causes and consequences of reported events in Rwanda. To analyse the possible consequences within the Bakokwe catchment, the following assumptions and methods were used:

- The proportions of causes and consequences reported on national level were used to estimate consequences within the districts of Muhanga and Kamonyi.

- The proportion of the total area of Muhanga and Kamonyi district that makes up Bakokwe catchment was estimated and used to estimate the numbers of lost livestock, lost hectares of crop, and damaged roads and bridges. The area of Muhanga and Kamonyi districts was then assumed to be equal, for the simplification of the assumption.

- The proportion of the total population of Muhanga and Kamonyi that lives within Bakokwe catchment was estimated based on the given population densities for Muhanga and Kamonyi districts, and the calculated population density for Bakokwe catchment, and used to approximate the number of lost lives and damaged properties.

- Roads and bridges were evenly distributed throughout the districts.

The estimated results were presented together with plotted rainfall data for the corresponding year.

Data that were retrieved from The New Times, BBC, New Humanitarian, ICRC and FEWS NET were structured and sorted for each time, duration and geographical position of an event. The events were classified into event periods where events overlapping in time and location and where reported by several media sources were defined as one event. The events reported in the districts covering Bakokwe catchment were assumed to happen in Bakokwe catchment and analysed together with corresponding rain data.

Results

Most of the previous studies on floods considered the upper part of the Nyabarongo catchment, a few considered the entirety of the Nyabarongo catchment, and only one focused on the Nyabarongo lower catchment (RWBa 2022). No previous studies solely on the Bakokwe subcatchment could be found. A potential explanation for this difference can be that the upper Nyabarongo catchment is considered highly prone to floods (Mind'je et al., 2019) and has a higher risk of erosion (Kulimushi et al., 2021) compared to the lower catchment. However, the Bakokwe subcatchment is located at the border between the upper and lower parts of the Nyabarongo catchment and thus close to the more flood prone areas (Mind'je et al., 2019).

In order to examine possible reasons behind reported floods and landslides, and to evaluate the situation of the Bakokwe catchment observed during the field visits, data on rainfall was evaluated. Since the rainfall data was gathered both from meteorological stations and satellite data, the different data sets had to be validated. This validation is presented in the first section of the result. The next section relates the results of the field visits to the relevant literature and the validated rainfall data, and aims to answer what effects of landslides and floods that can be observed in the Bakokwe catchment. Following this is a section assessing the agricultural practice, land use and land cover of the catchment, in order to investigate if land use practices might imply a change in flood and landslide occurrence. Then, two sections that relate the susceptibility to floods and erosion and landslides follows, which discusses the vulnerability of the catchment. Lastly, the reported disaster events over Rwanda and the Bakokwe catchment are presented respectively. The events that had specific dates and could be assumed to have occurred in the Bakokwe catchment are accompanied by estimations of the rainfall. The reports are presented first on a national level, and then over the Bakokwe catchment, in order to convey the history of occurrence and impacts of floods and landslides in the area.

Validation of rainfall data

Most of the reviewed literature mention the lack of rainfall data as an essential area of improvement to enable good hydrological research in the country. As the variability of rainfall throughout the country is high (Siebert et al., 2019), it is important to get accurate data on the occurrence, intensity, and duration of rainfall events. Different methods have been used to fill in the gaps of data in the Nyabarongo and Bakokwe catchments, such as linear regression (Mikova et al., 2015) and a combination of several rainfall estimate sources (Ndekezi, 2010). In this thesis, the main gap was the lacking data of 2022. No data was available from the meteorological stations and satellite data was therefore used. The Nyabarongo catchment contains 25 meteorological stations, which are presented in Figure 6.

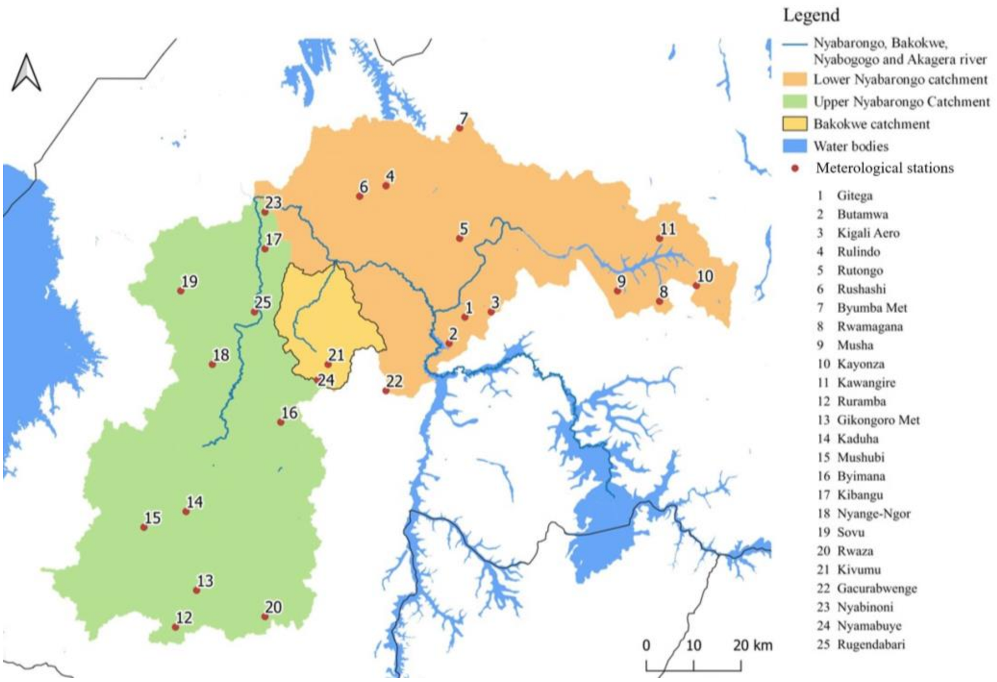


Figure 6. Meteorological stations in the upper and lower Nyabarongo catchment. Bakokwe catchment is illustrated in yellow and contains two meteorological stations.

The meteorological stations are spread throughout the Nyabarongo catchment and some of them are located close to the Nyabarongo river. The country has historically had a high number of working rain gauges covering big parts of the country, in 1960 the country had more than 140 working gauges and in 1990 about 130. This changed in the aftermath of the genocide in 1994 when a lot of infrastructure was destroyed, and in 2006 the country only had 11 working rain gauges (Ndekezi, 2010). Today, the amount of rain gauges have increased and there are about 100 hydrological stations throughout the country (RWBa, 2022; Siebert et al., 2019). These stations get vandalised occasionally and also experience damages by weather induced forces and thus do not always operate at full capacity (personal contact with Mr. Davis Bugingo, 2022). On average, each district in the country has 2.5 stations each and the area each station covers, on average, an area of 350 km2. The number of hydrological stations with available rain data (retrieved from METEO) in the Nyabarongo catchment differed between 1980 and 2019. The number of stations with available data for 1980-2019, are presented in Figure 7, which was used to evaluate the available data and retrieved result.

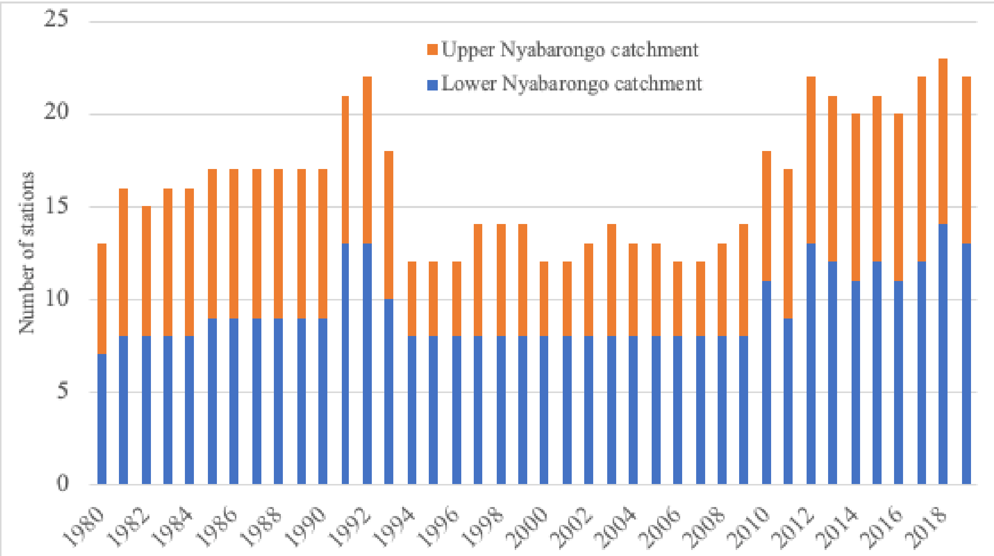


Figure 7. The number of hydrological stations with available data in the lower and upper Nyabarongo catchment between 1980-2019 (data from METEO, 2019).

Figure 7 shows a lower number of operating meteorological stations for the period of 1994-2010, the period after the genocide. Both the upper and lower catchment follow similar trends, with an increasing number of operating stations with data from 1990 to 1994 and from 2010. Figure 7 shows a total of 12 stations with available data in 2006, which contradicts the literature, which mentions 11 functioning rain gauges nationwide that year (Ndekezi, 2010). Two of the meteorological stations are located within the Bakokwe catchment and both had complete and reported rainfall data between 1981-2019, whilst no data for 1980 were available. Since the results shown in Figure 7 does not take into account shorter periods of lacking data, which can be up to 6 months, the numbers presented in Figure 7 might be overestimated, which would be more in line with what is presented by Ndekezi (2010). Also, no information was available on if or how the rainfall data from METEO was processed. If periods of missing data have been registered as zero rainfall, which would have influenced the presented number of operating stations and the evaluated average data presented.

The satellite data was validated against the data from the rain gauges for two-week averages during the period 1983-2021. The R^2-values at each location are presented in Table 4, and the fit and 95% confidence bounds of the regression analysis is presented in Figure 8.

Table 4. The R^2-values of the regression analysis for the evaluated stations, together with the minimum, maximum and mean R^2-values. The stations in Bakokwe (ID21 & ID24) are marked in bold.

Station ID	**R^2**	**Station ID**	**R^2**	**Station ID**	**R^2**	**Station ID**	**R^2**
1	0.14	9	0.19	17	0.10	25	0.081
2	0.17	10	0.13	18	0.15		
3	0.18	11	0.29	19	0.10		
4	0.12	12	0.19	20	0.18		
5	0.17	13	0.069	**21**	**0.085**		
6	0.31	14	0.11	22	0.14	Min;	0.039
7	0.14	15	0.15	23	0.15	Max;	0.31
8	0.22	16	0.14	**24**	**0.039**	Mean;	0.15

The R^2 values vary between 0.039 and 0.31, and the mean value indicates that about 15% percent of the gauge data can be explained by a linear relationship between the satellite and rain gauge data. This is not a strong correlation, and satellite data should thus only be seen as an indication rather than an accurate description. As can be seen in Table 4, the satellite data for the two stations in Bakokwe subcatchment (ID 21 and 24), are not reliable. Nevertheless, the other stations in the area around were used to interpolate the precipitation over the Bakokwe catchment for 2022, for which no rain gauge data was available. Throughout the use of the satellite data, care was taken to not put too much weight on the result of the normalised satellite data but to only use it as an indication, as the regression shows such low R^2-values. In Figure 8, the scatter plots of the stations with a R^2-value higher than 0.15 are presented.

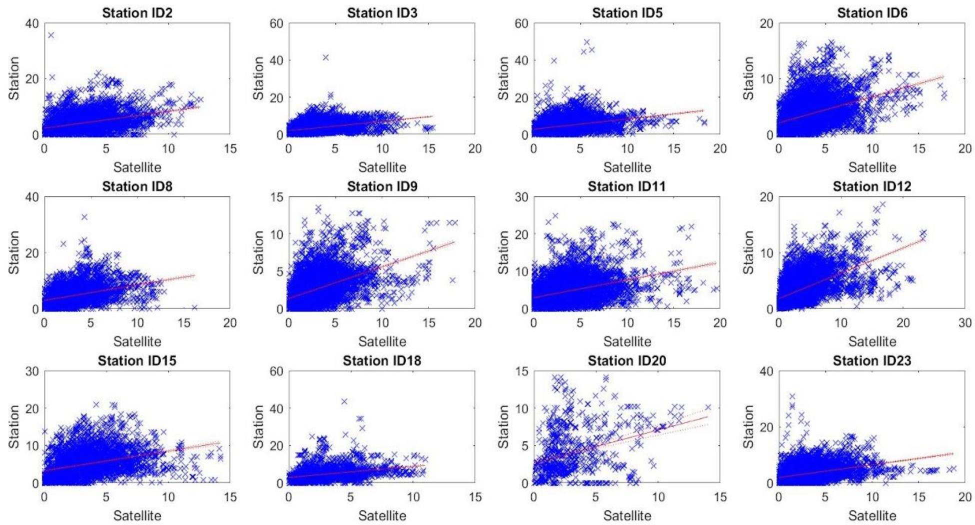


Figure 8. Result of the regression from station 2, 3, 5, 6, 8, 9, 11, 12, 15, 18, 20, and 23. The blue crosses represent data points, the red solid line the fit and the dotted red lines the confidence interval.

Figure 8 illustrates the result of the regression, and depending on the station the data are moderately to highly spread out. It can be seen that the rain gauges record peak precipitation that is not captured by the satellite database, which indicates that the satellite data might record a lower value of precipitation than the rain gauges.

Site visits

Observations of the site visits are presented in the following section for each of the chosen locations together with related results from the literature review. Corresponding rainfall data for each of the locations and date is also presented, from one week prior to the date of the field visit, as the calculated travel time for surface runoff in the catchment was around 2-5 days depending on distance travelled. Figure 9, shows the general patterns of land use, river appearance and topology of the catchment.

Figure 9. Pictures taken of the Bakokwe catchment during the site visits, on the 21st, 22nd of February and 1st of March 2022.

As seen in the pictures presented in Figure 9, the parts of the Bakokwe catchment that were assessed during the site visits were characterised by a hilly landscape with steep slopes and rural areas with sparse settlements. There were gravel roads connecting villages and towns with visible marks of erosion and sediment transport. The majority of the bridges crossing the rivers and streams were damaged or had been temporarily repaired. The land was mainly covered by agricultural land where crops such as banana, cassava and maize were grown. About 14% of the district of Kamonyi are covered by progressive terraces which are implemented to prevent erosion in the farmlands (Kamonyi district, 2018) and this was confirmed by the field visits as some terraces could be seen. In Muhanga district, only about 1% are covered by terraces (Muhanga district, 2018) and this was observed during the field visits as less terraces could be seen when visiting Muhanga district than Kamonyi district. There were tributary streams and rivers meandering in the valleys and some of the large rivers had wide floodplains. Most of the rivers were characterised by high sediment load, erosion and deposit of sand, stones, and rocks.

Several mining facilities were identified during the field visit, and indications of illegal mining were also observed. This was expected as the main incomes in Muhanga district is, except for the agricultural products, mining for wolfram, coltan and cassiterite (Muhanga district, 2018). Kamonyi district does not have as many mining activities as the district of Muhanga, but does also perform mining for wolfram, coltan and cassiterite. Furthermore, the district of Kamonyi has a large amount of sand, stones and clays that are used for construction (Kamonyi district, 2018) and such excavations were also observed during the site visits. Agriculture is the main occupation of the land in the district of both Muhanga and Kamonyi, where the main crops are maize, beans, cassava, rice, soybeans, vegetables and bananas and in the marshlands, farmers cultivate tomatoes, vegetables, maize and sugarcane (Muhanga district, 2018); (Kamonyi district, 2018). The natural flora and fauna have been depleted as the high population increase has favoured agricultural land and activities (Kamonyi district, 2018) which the observations throughout the field visit verified.

The rainfall one week prior to the field visit was normalised compared to the historical rainfall that period and are presented in Figure 10, together with the field observation points.

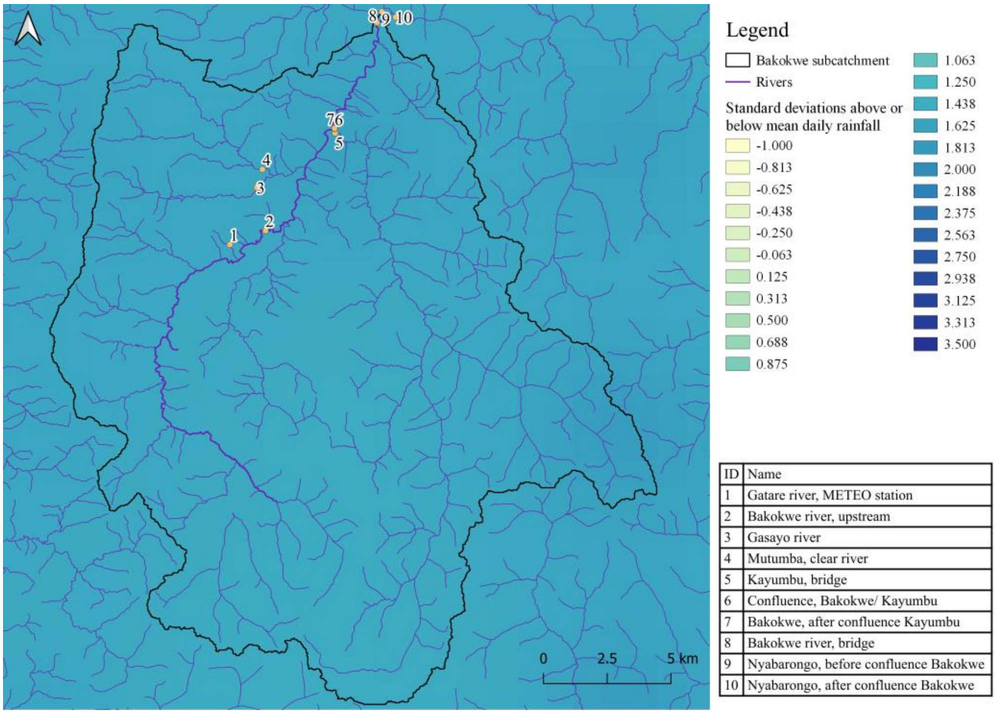


Figure 10. Shows the normalised daily average rainfall over the Bakokwe catchment over the period of 14th of February to the 1st of March 2022 (data from ARC2, 2022), the observation points are marked with its respective ID. Normalised on the historical period 14th February-1st March, every year from 1983 to 2021.

The result presented in Figure 10 shows that the precipitation prior to, and at the time of the field visits, was higher than normal in the entire catchment. The rainfall was between one and two standard deviations higher than normal, and it is thus likely that the water levels and runoff of the catchment was higher than they usually are at that time, and that the soil was saturated with water.

Gatare river

The Gatare river is a tributary of the Bakokwe river and had a meteorological station located at the first observation point, in Figure 5 this location was indicated as point number 1 and is situated in Muhanga district. Pictures of the location are shown in Figure 11.

Figure 11. The Gatare river with its surrounding landscape, on the 21st of February 2022.

A crossing bridge over the Gatare river was connecting two gravel roads and had clear signs of temporary repairs. The bridge was estimated to be located 3 meters above current water level. According to local inhabitants interviewed during the field visits, the water level in the river has previously exceeded and damaged the bridge and flooded the surrounding agricultural land. There were steep slopes and extensive erosion in direct contact with the river bed. The agricultural land covering the surrounding landscape was mainly banana plantations, maize, cassava, sparse eucalyptus trees, and moderate grassland. There was a small number of terraced plantations.

Bakokwe river, upstream part

Downstream the measuring point of the Gatare river, the second point of measurement in the Bakokwe catchment was situated (see Figure 10). Pictures of the surroundings of the measuring point during the measurements are presented in Figure 12.

Figure 12. Photographs from the second observation point when the measurements were taken at this location on the 21st of February 2022.

At this location and time, the river had a wide floodplain with low water levels and the river was divided into two smaller streams, one in the south part and one in the north part of the river bed. There were clear signs of erosion in direct contact with the river and of deposition of sand, stones, and blocks along the river bed. The steep and eroded slopes were estimated to be 2-3 metres high. The agricultural land was mainly covered by banana plantations, maize, sparse eucalyptus plantations, smaller crops, or grassland. There were no or few terrace plantations. Measurement results of water velocity, water depth and river cross section are presented in Table 5. The north part of the river bed was narrow and shallow while the south part of the riverbed was wider.

Table 5. The results of the measurements in Bakokwe river upstream on the 21st of February 2022.

	Width of river (m)	**Average water depth (m)**	**Cross section (m^2)**	**Velocity (m/s)**	**Discharge (m^3/s)**
North part	4.4	0.058	0.32	0.68	0.18
South part	6	0.34	2.41	2.84	5.82

Confluence point of Bakokwe and Kayumbu rivers

The third observation spot was in the area of the confluence of Bakokwe river and Kayumbu river, which is a tributary of Bakokwe river, and is situated in Kamonyi district. In Figure 13, pictures from the location are presented.

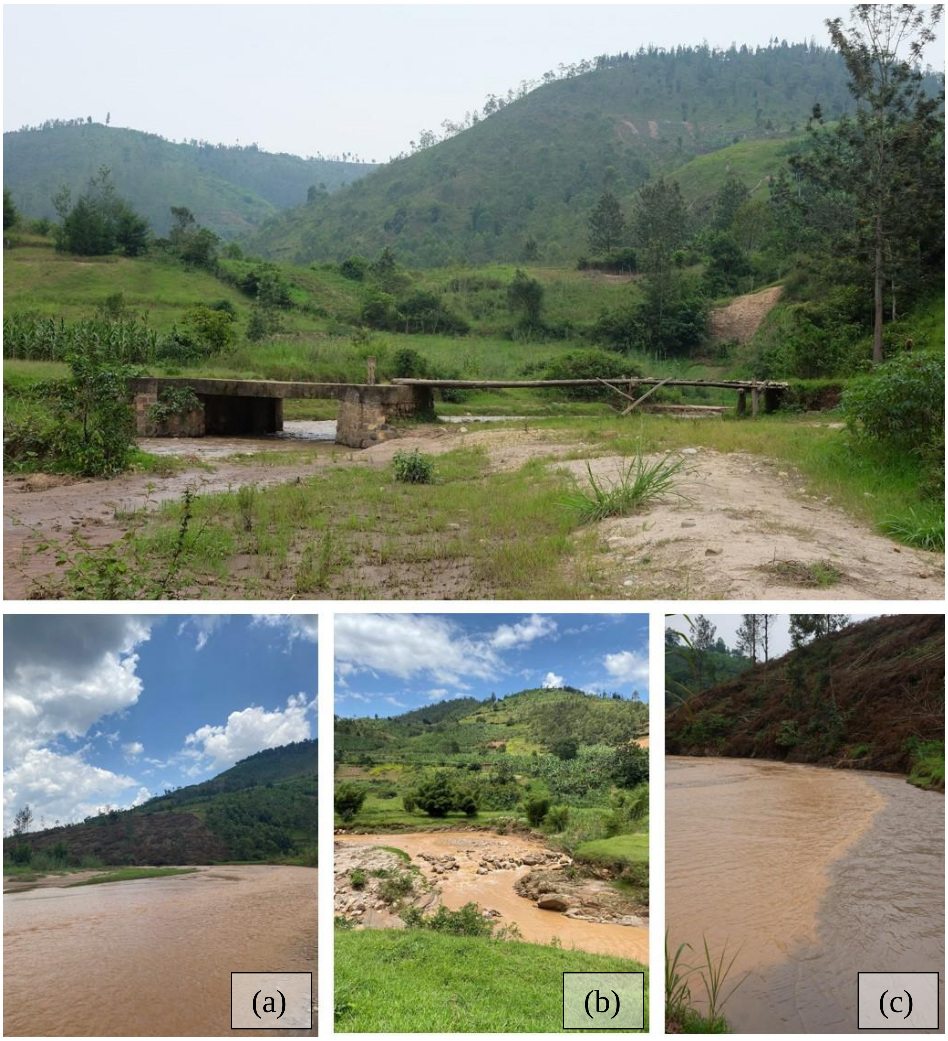


Figure 13. Photographs from downstream of (a), upstream of (b) and at (c) the confluence between Kayumbu and Bakokwe rivers on the 21st of February and the 1st of March 2022. A bridge crossing Kayumbu is shown in the top part of the figure. The lower part of the figures shows Bakokwe river upstream of the confluence as well as the actual confluence point.

In the area of the confluence point of Bakokwe river and Kayumbu river, the croplands were dominated by cassava and banana plantation. There were also clear signs of deforestation on steep sloping hills along both rivers, which can be seen in the lower right part of Figure 13. Most houses and settlements were situated on hillsides. There were visible deposits of sand, stones, and rocks as well as a wide floodplain, mainly upstream the Bakokwe river. A bridge which was crossing the Kayumbu river had been temporarily repaired. Interviews with five local inhabitants, one of them the mayor of the village situated nearby, indicated that the bridge had been damaged by increased water levels and floods. A visible changing floodplain had made the locals expand the bridge approximately 7-10 meters to adjust for higher water levels and a wider river cross section in the past years.

At the confluence point of Bakokwe river and Kayumbu river there was a significant difference in colour of the water which can be seen in Figure 13, with Bakokwe river having a stronger red and brown colour. The local inhabitants of the nearby village used to drink the water of the Bakokwe river but are no longer able to, since the sediment load had increased. The interviewed local inhabitants of the village indicated that the upstream city of Muhanga was one of the reasons the water was polluted.

Gasayo river

The fourth location of observation was chosen to be close to a bridge crossing the Gasayo river, which is a tributary to the Bakokwe river, and is located in Muhanga district. Pictures taken at this location are shown in Figure 14.

Figure 14. Photographs from the Gasayo river on the 1st of March 2022.

The Gasayo river is a narrow stream, referred to as the "dirty river" in the area and was by the time of the site visit characterised by its red and brown colour. The surrounding area upstream the bridge was steeply sloping and covered with agricultural land, mainly maize on the low lying land close to the river bed and cassava and sparse eucalyptus trees on terrace plantations. There were broken protective structures and clear signs of erosion and deposition of sediment directly upstream the bridge, which can be seen in Figure 14. The bridge was estimated to be situated 3 meter above water level at that time. Downstream of the bridge, low lying crop land with cassava, maize and grassland was grown close to the river which can be seen in Figure 14.

Bakokwe river, bridge

Close to the outlet of the Bakokwe river into the Nyabarongo river is a bridge which was chosen as the fifth location for measurements and observation. This location is situated just on the border between Muhanga and Kamonyi districts. In Figure 15, pictures of the location, the Bakokwe river and the bridge at this location can be seen.

Figure 15. Photographs of the Bakokwe river and the bridge crossing it, pictured from different angles, on the 21st and 22nd of February 2022.

At this location, the surrounding area was characterised by a wide floodplain surrounded by cassava plantations, sparse bamboo trees, low lying, and grass covered land as well as steep sloping hills with banana and pineapple plantations, as can be seen in Figure 15. The bridge connected two gravel roads and had over the past years been flooded several times according to local people. The width of the bridge was assumed to be the same as the width of the river. Measurement results of velocity, cross section, width of bridge, and height of bridge are presented in Table 6.

Table 6. The results of measurements at Bakokwe river bridge during the 21st and 22nd of February 2022.

Width of bridge (m)	**Estimated height of bridge above water level (m)**	**Average water depth (m)**	**Velocity (m/s)**	**Cross section (m^2)**	**Discharge (m^3/s)**
17.1	1	0.54	1.57	8.58	11.49

At this location, pictures were taken by a local resident that was hired for the purpose of observing changing water levels. The pictures were taken and sent when noticeable increases in water level of the Bakokwe river occurred. The results of this are presented in the following section.

Reported water levels, February to April 2022

Pictures were taken on the 25th of February, 22nd of March, 3rd of April and on the 16th of April 2022 by one local resident. The width of the river, just under the bridge, was assumed to be constant and was the point where the discharge was estimated. This assumption was considered valid during all dates that pictures were taken. The velocity was also considered to be constant at all reported events. In Figure 16, the pictures taken on the 25th of February 2022 are shown. The water level was estimated to be one meter below the bridge based on the observations of the pictures.

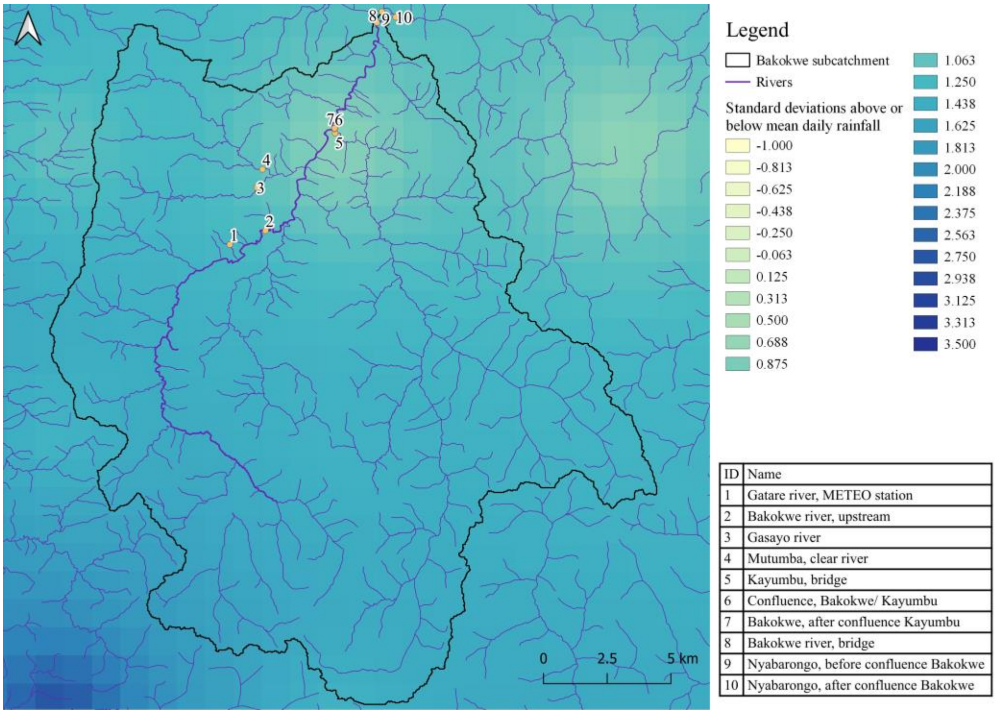
Figure 16. The Bakokwe river and bridge the 25th of February 2022 (pictures from local resident, 2022).

The river's water surface had not changed significantly compared to when the field visit was conducted. The depth was approximated to be the same as on the 22nd of February. Thus, the flow of Bakokwe river on this location was estimated to be 11.49 m^3/s on the 25th of February 2022. The normalised mean daily rainfall data from one week prior to, and including, the 25th of February was presented in Figure 10, where it could be seen that the precipitation of the Bakokwe catchment was higher than normal. Especially closer to the boundaries of the catchment, the precipitation was about 1.7-2 standard deviations above normal. As the Bakokwe bridge is close to the outlet of the Bakokwe river into the Nyabarongo river, where all water that have drained the catchment flows out, it is reasonable to assume that the high water level of the Bakokwe river is due to the above normal rainfall during the previous weeks.

Pictures taken on the 22nd of March 2022 are shown in Figure 17 and shows an increase in water level. The water level was estimated to be 0.4 meter below the bridge at that time.

Figure 17. The Bakokwe river and bridge the 22nd of March 2022 (pictures from local resident, 2022).

The bridge was close to becoming covered by the river's water surface in Figure 17. The estimation of the river depth suggests that the water level and width of the Bakokwe river, on the 22nd of March, was 1.14 and 17 metres respectively. Thus, the cross section area was estimated to be 19.4 m^2 and the flow on this day was thereby estimated to be 30.4 m^3/s. The normalised mean daily rainfall data, one week prior to this occasion is plotted in Figure 18.



ID	Name
1	Gatare river, METEO station
2	Bakokwe river, upstream
3	Gasayo river
4	Mutumba, clear river
5	Kayumbu, bridge
6	Confluence, Bakokwe/ Kayumbu
7	Bakokwe, after confluence Kayumbu
8	Bakokwe river, bridge
9	Nyabarongo, before confluence Bakokwe
10	Nyabarongo, after confluence Bakokwe

Figure 18. Normalised rainfall over the Bakokwe catchment one week prior to, and during, the 22nd of March (15th of March to the 22nd of March 2022) (data from ARC2, 2022). Normalised on the historical period 15th March- 22st March, every year from 1983 to 2021.

As can be seen in Figure 18, the mean daily precipitation during the week leading up to the reported high water level of Bakokwe river, was higher than normal, especially in the southern parts of the catchment which is the upstream part. The precipitation falling in the upstream parts of the catchment drains down in the Bakokwe river and reaches the Bakokwe bridge in the northern parts of the catchment in 2-5 days. Higher water levels than normal were thus expected, which the reported high level indicates.

On the 3rd of April the water level was approximately 0.8 meter below the bridge. Thus, the cross section on the 3rd of April was estimated to be 12.6 m^2 and the flow to be 19.8 m^3/s. Figure 19 shows the situation on the 3rd of April.

Figure 19. The Bakokwe river and bridge on the 3rd of April 2022 (pictures from local resident, 2022).

On the 3rd of April, much of the riversides were covered and the water was close to breaching them, which can be seen in Figure 19. The normalised mean daily rainfall one week prior to the 3rd of April was calculated to compare it to the increase in water level, which is shown in Figure 20.

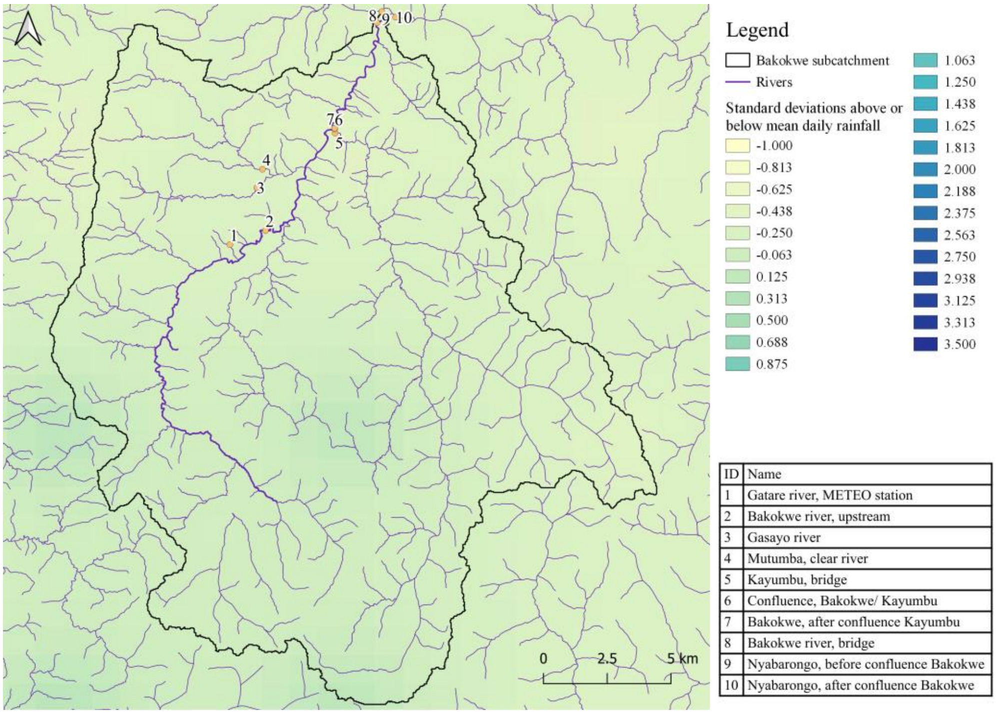


Figure 20. Shows the normalised rainfall over the Bakokwe catchment one week prior to the 3rd of April (24th of March to the 3rd of April 2022) (data from ARC2, 2022). Normalised on the historical period 24th March- 3rd April, every year from 1983 to 2021.

The normalised daily rainfall presented in Figure 20 shows that the rainfall leading up to the 3rd of April 2022 in general was below normal in the Bakokwe catchment. A few areas in the upstream parts of the catchment experienced normal rainfall, and a few areas just a bit above normal. However, this indicates that it was not abnormally intense rainfall that was the reason for the high water levels in the Bakokwe river on the 3rd of April. The reason for the high water level is more likely to have been rainfall over the previous months, which would have saturated the soil and increased the water level to a constant height. Lastly, on the 16th of April the water level was reported to have increased again. At this time it was estimated to have reached a level of

1.2 meter below the bridge and this resulted in a cross section of 5.8 m^2. Thus the flow was estimated to be 9.1 m^3/s on the 16th of April. In Figure 21, the water level is shown.

Figure 21. The Bakokwe river and bridge on the 16th of April 2022 (pictures from local resident, 2022).

The water level shown in Figure 21 was the lowest one recorded out of the reported rises of water level. In Figure 22, the normalised daily rainfall one week prior to this recording is presented.

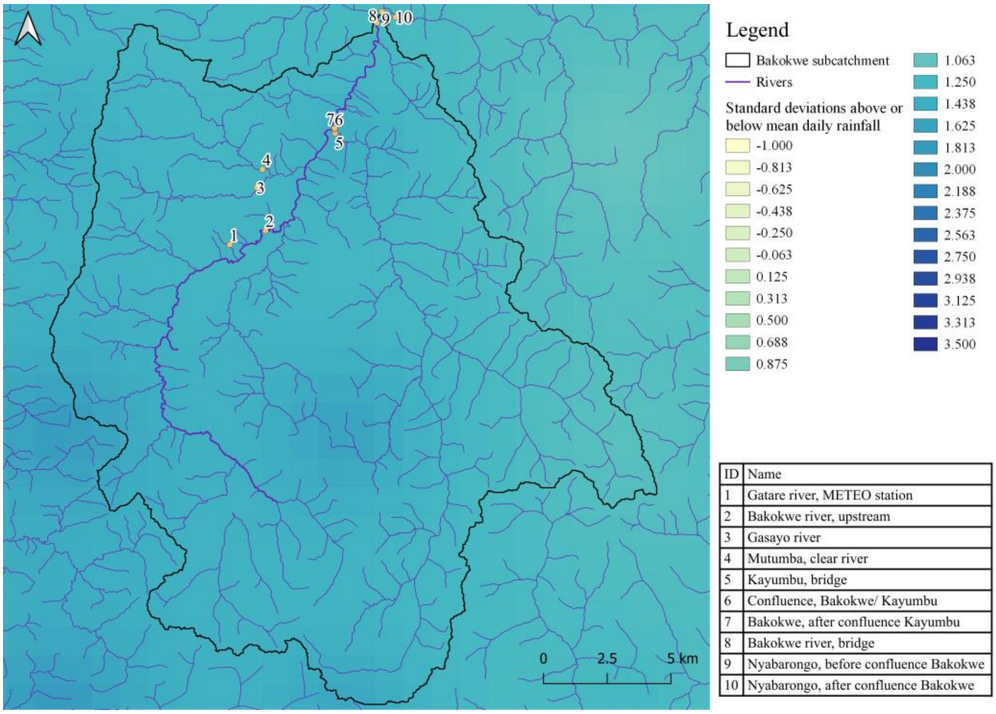


Figure 22. Shows the normalised mean daily rainfall over the Bakokwe catchment one week prior to the 16th of April (9th to the 16th of April 2022) (data from ARC2, 2022). Normalised on the historical period 9th April- 16th April, every year from 1983 to 2021.

The normalised daily rainfall presented in Figure 22 shows that it had been raining between 1 and 1.8 standard deviations above normal. This, together with the above normal daily precipitation in February and beginning of March were possible contributing reasons to the remaining high water levels in the Bakokwe river. All estimated flows are presented together with the corresponding estimated standard deviation of the normalised rainfall in Table 7.

Table 7. The estimated flows at the Bakokwe bridge and standard deviations of rainfall above or below normal for the Bakokwe catchment for the five observed occasions.

Date	**2022-02-22**	**2022-02-25**	**2022-03-22**	**2022-04-03**	**2022-04-16**
Estimated flow [m^3/s]	11.49	11.49	30.4	19.8	9.1
Estimated standard deviation of rainfall	0.95-1.1	0.95-1.1	0.1-2.3	-1-0.9	0.4-1

The compiled result of the estimated flows and deviation of rainfall from normal presented in Table 7 indicates that the response time of the river is about one week, since the above normal rainfall that fell over the catchment from the 14th of February to 1st of March 2022 and 15th of March to the 22nd of March affected the flow approximately with one weeks delay. After the 22nd of March, the rainfall was normal in most parts of the catchment for the time leading up to the 16th of April. This gave a response in the river flow, as it was slowly decreasing and registered the lowest values on the 16th of April.

Mutumba river

The sixth location for measurements and observations was a tributary to Bakokwe called Mutumba, situated in Muhanga district. This river is known as the ‘clear river’ in the area, and a clear difference in the colour of the water at the time of the site visit was observed compared to the other locations. The river and its surroundings can be seen in Figure 23.

Figure 23. Photographs of the Mutumba river and its surroundings.

At this location, a bridge was crossing the river and connecting two gravel roads. The bridge was estimated to be located 2.5 meter above the water level. The area surrounding the river bed was low lying, flat, grass covered, and used for rice cultivation, which can be seen in Figure 23. Sparse to moderate forest was growing on the surrounding steep sloping hills. This gave a clear indication that the land use around a river influences the quality of the water as well as the susceptibility to erosion, since this location differed in land from the other locations, and had both clear water and no visible signs of erosion.

Land use and agricultural practice

Human population increase and agricultural expansion are two of the main drivers for land use change and deforestation in the Bakokwe subcatchment as well as in Rwanda. In 1990, 44% of the surface of the country was covered by forests (Karamage et al., 2016). The forest cover in the two districts sharing Bakokwe subcatchment, Kamonyi and Muhanga districts, differs slightly. Kamonyi district is one of the least forested rural districts, with a forest coverage of only about 14% of the district in 2019 according to the Rwanda Forest Cover Mapping (Ministry of Environment, 2019), and only about 11% according to the Kamonyi District Development Strategy (2018). According to the Muhanga District Development Strategy (2018), the area covered by forest in Muhanga district was only 6% in 2017. Data from the World Bank (2020) contradicts the findings in the Rwanda Forest Cover Mapping (Ministry of Environment, 2019) and presents a national forest coverage of only 11.2% in 2020, whilst the Global Forest Watch (2022) states that forest covered approximately 18% of Rwanda in 2015.

Adding to the low coverage of natural forest and planted forests in the districts covering Bakokwe, and generally in Rwanda, is the spread of unsustainable land use practices and unplanned settlements, which is induced by high population density and the heavy dependency on agriculture. The unplanned settlements forming in the country lack necessary infrastructure due to both the unplanned and unrestricted way that the settlements have grown and because the government is avoiding creating sufficient infrastructure in these areas (Karamage et al., 2016).

The agriculture of Rwanda is of high importance to the economic growth of the country as well as for the provision of sustenance to the people of the country. Much research has been done on agricultural practice in the country and the productivity per unit land has increased due to research on new crop varieties (Gahakwa et al., 2014). As the country is one of the most densely populated countries in Africa, its agriculture is constrained by the available land and it is dominated by smallholder farmers (Mikova et al., 2015) with an average crop land of 0.7 ha/household (Gahakwa et al., 2014). The density of cropland varies along the country and in the Nyabarongo catchment the density is high. The 2019 Rwanda Forest Cover Mapping (Ministry of Environment, 2019) also showed deforestation in the area between the years 2009 and 2019 as well as the tree cover density being low in most parts of the two districts that share the Bakokwe subcatchment, which was confirmed by during the field visits at the observation points. The low density indicates that the forest mapped likely consists of tree plantations rather than natural forests which were validated during the field visits, as no natural forests could be observed. Dense forests have a high capability of decreasing erosion and thus also in decreasing the consequences of floods (National Geographic Society, 2018), this important feature has thus been lost in the Bakokwe subcatchment due to the low amount of dense forests.

Land cover maps of Bakokwe catchment, produced by the Regional Centre for Mapping of Resources for Development (RCMRD) in 1990, 2000, 2010 and 2015 are presented in Figure 24 together with land cover maps for the years between 2017 and 2021 produced by the ESRI in 2022. In Figure 24, the land cover of year 2020 is represented twice where the first map, denoted 2020a, is the map produced by ESRI, the second denoted 2020b are the one produced with satellite imagery.

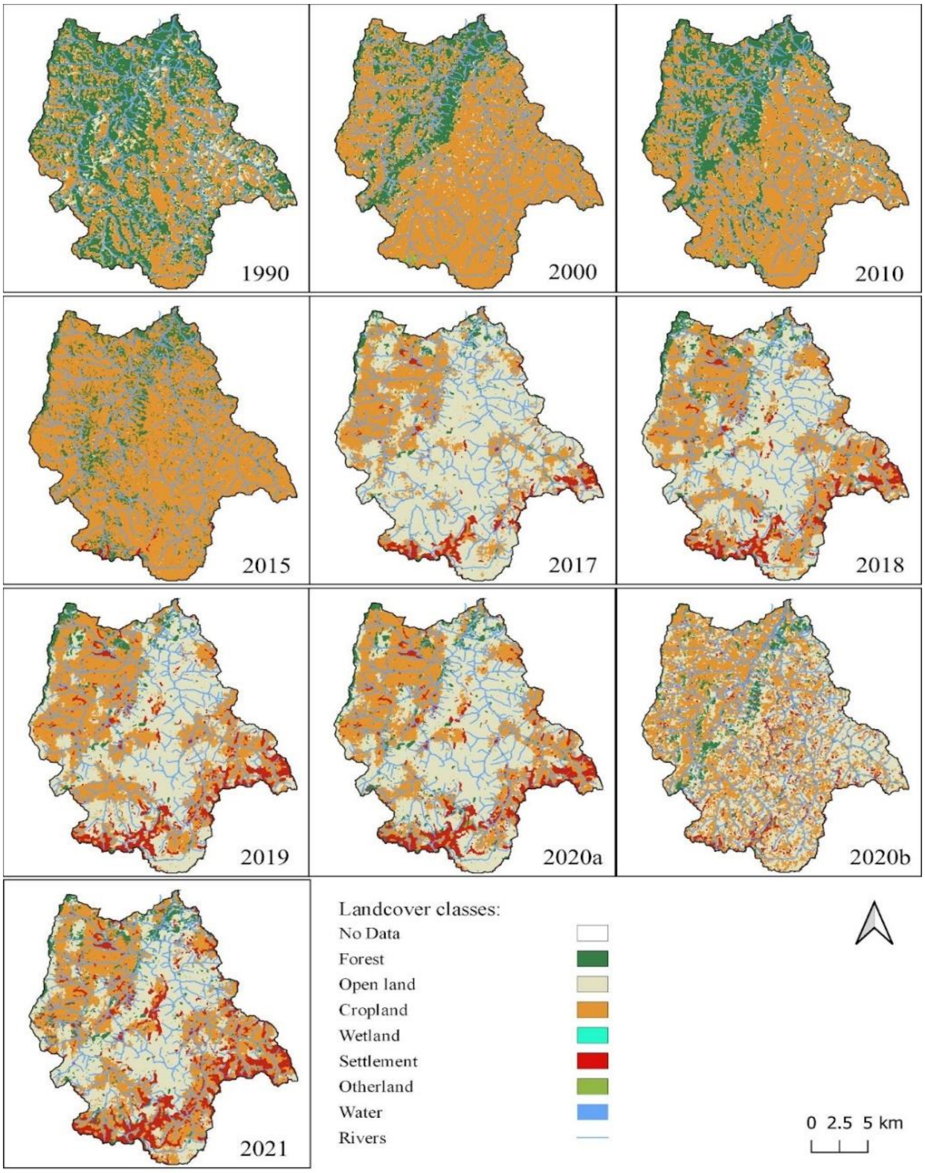


Figure 24. Land cover in Bakokwe catchment for the years 1990, 2000, 2010, 2015 (data from RCMRD, 2015), the years 2017, 2018, 2019, 2020a, 2021 (data from ESRI, 2022) and 2020b (data from Landsat 8, 2022).

The land cover changes presented in Figure 24 shows that a large part of the forests that existed in 1990 have been removed in favour of cropland. Most of the forest that remained in 2000 was centred around the Bakokwe river and between the years 2000 and 2010 it seems that the forestland had increased in area, before decreasing further to below 2000-levels in 2015. Figure 24 also shows the extent of grasslands has been reduced over this period.

Between 2015 and 2017, the results in Figure 24 indicates that much of the cropland in 2015 became grassland or rangeland in 2017. One explanation to this is an inaccuracy due to the change in method for producing the land cover maps between the years. The spectral reflectance of agricultural land and grassland are similar, thus it is possible that the two might have been difficult to distinguish between. The maps between 2017 and 2021 are produced by ESRI with reliable methods whilst the maps produced by the RCMRD in the years before are based on less material and data. During the years 2017 to 2019, settlements and cropland expanded whilst forest- and grassland decreased.

Comparing the results of the 2020 maps with the map from 2015 it can be seen that grassland has increased and that forestland has continued to decrease. The image 2020b deviates from the 2020a one, where the labelling of settlements in the southern and eastern part as water and some rivers as settlements are the most noticeable. This is due to the similarity in spectral reflectance of the two land classes and that the trained software is unable to distinguish between those based on the training samples. The results of map 2020b in Figure 24 presents a different result from the land cover that ESRI produced for the year of 2020 which is presented as map 2020a in the same figure. It can be seen that the forestland is very sparse in the year 2020 and that we have a clear divide between the cropland and the rangeland. Furthermore, settlements have expanded to a bigger area in the result in map 2020a compared to the map 2020b in Figure 24. Some areas that in map 2020b are classified as forestland are in map 2020a classified as cropland. The results of map 2020a seems to underestimate forestland and possibly also cropland, while overestimating settlements. On the other hand, the map 2020b underestimated settlements and possibly overestimated cropland. The two do not contradict each other but rather complement each other, indicating the difficulties in using satellite imagery to map land cover. The result of both 2020a and 2020b are that little forest cover exists, and that cropland or open land dominates the cover of the catchments' surface.

The five years between 2017 and 2021, illustrated in Figure 24, shows an increase in built up areas in the southern and northern parts of the catchment as well as an increase in cropland. Compared to land cover in 1990, almost all forestland has disappeared from the catchment. The percentage of each land cover class is presented in Table 8, which gives a clear indication that significant deforestation has taken place between 1990 and 2015 in favour of the expansion of cropland and built up areas. The percentage of forestland has decreased from 14 to 6% between 2015-2021. One contributing factor to the large decrease in forest cover is the use of different sources in 2015 compared to 2017-2021. Assuming that open land and cropland both make up agricultural land, Table 8 shows that the percentage of agricultural land has been stable since 2015 while the percentage of settlements increased significantly between 2015 and 2017. During the 25 years between 1990 and 2015, the decrease in forest cover and density gave place to agricultural land, while after 2015 it mainly gave place to settlement.

Table 8. Percentage of land cover classes, analysed with zonal histogram in QGIS. Data for the years 1990 to 2015 are from RCMRD, data for the year 2017 to 2021 are from ESRI. The year 2020 has two analyses, both of which are presented here. 'ESRI' indicates the data from ESRI, 'Sat.' the analysis made from Landsat 8 images.

	1990	**2000**	**2010**	**2015**	**2017**	**2018**	**2019**	**2020** *ESRI*	**2020** *Sat.*	**2021**
Forest [%]	16	6.4	9.4	14	3.6	5.5	4.5	5	6.4	6
Open land [%]	5.2	2	2.7	0.75	63	48	45	49	40.6	41
Cropland [%]	13.7	26.5	22.8	84.7	29	39	41	36	44.4	39
Agricultural land [%]	*18.9*	*28.5*	*25.5*	*85.4*	*92*	*87*	*86*	*85*	*85*	*80*
Wetland [%]	0	0	0	0	0	0	0	0	-	10^{-5}
Settlement [%]	0.14	0.57	0.26	0.43	4.9	7.6	9.4	8.7	5.98	14
Water [%]	-	-	-	-	0	0	0.001	0.01	2.66	0.02

However, the percentage of forestland has been on similar levels from 2018 and forwards, only varying a few percentages which might be the result of different fertile conditions each year or only a small amount of de- or afforestation. The percentages presented in Table 8 further indicates a general underestimation of water and flooded vegetation, as several floodplains and plenty of rivers were observed during the field visit.

Susceptibility to floods

Simulated floods in the downstream part of the upper Nyabarongo catchment indicates that the 10-year flow is 800 m^3/s, the 50-year flow is 21 000 m^3/s, and the 100-year flow is 55 000 m^3/s is predicted (Kwisanga, 2017). As Bakokwe subcatchment is located just on the border to the downstream part of the upper Nyabarongo catchment, these flows will most likely affect Bakokwe subcatchment and might induce riverine floods. To put these flows in perspective, the hydropower plant which is located upstream of the Bakokwe outlet in Nyabarongo, can handle a maximum flow of about 55 m^3/s (Hakizimana et al., 2020). Thus, flows of 800 m^3/s would increase the flow in the river with about 15 times the current maximum flow capacity. This might lead to severe consequences and flooding of large parts surrounding the Nyabarongo river, including the area of Bakokwe. The likelihood of the consequences of flood events were answered by the four respondents of the questionnaire and are summarised in Table 9. The full answers are presented in Appendix A.3.2.

Table 9. The average score of the answers to question 7-10 in the questionnaire. All questions asked, searched the answers to how likely it is that floods cause the scenarios presented in the table. The numbers 1-6 correspond to the following perception: 1 = Not likely, 2 = Possible, 3 = Likely, 4 = Very Likely, 5 = Most Likely, 6 = Certain.

Reduction in agricultural productivity?	Roads to become impassable/ non-usable?	Loss of human lives?	Damage to house property?
4 (very likely)	3 (likely)	2.5 (possible/likely)	3.25 (likely)

According to summarised answers of the respondents, floods in the Bakokwe subcatchment and the Nyabarongo catchments are very likely to cause reduction in agricultural productivity, and are likely to cause roads to become impassable, damages to house and properties and that it is possible or likely that loss of human lives occur as a consequence of floods in the area.

It is complex to map the flood susceptibility as it depends on several factors such as the topography, geomorphology, drainage capacity, built-up structures, rainfall frequency, intensity, duration, and population density (Mind'je et al., 2019). The susceptibility varies in different parts of the Nyabarongo catchment due to changes in the mentioned factors.

The geological characteristics in Bakokwe catchment are a combination of humic nitisols and ferralsols, umbric and haplic acrisols, dystric cambisols and cambic umbrisols (Jones et al., 2014), while the geomorphological characteristics are steep slopes, porous material, impermeable material, erosion, and hilly terrain (RWBa, 2022). The main vegetation in the catchment are agricultural plants such as maize, banana and cassava and the drainage capacity is generally limited (Muhanga District, 2018; Kamonyi, 2018), due to the soil type, the vegetation cover and the built structures, and the area experiences as heavy and intense rainfalls as the upper Nyabarongo catchment (Mind'je et al., 2019).

The respondents of the questionnaire were asked if they had identified any area in the Bakokwe subcatchment and Nyabarongo catchment that are more exposed to floods than other areas. Mr. Ezechiel Niragire, environmental and social safeguards specialist in the Muhanga District, specified the agricultural land along the Nyabarongo and Bakokwe rivers, and roads and bridges as the areas mostly exposed to floods. The areas identified by Mr. Nzabahimana James, water and sanitation officer at the Kamonyi district, and Mr. Alphonse Hishamunda, Ag. Director of the prevention and mitigation unit at MINEMA are shown in Figure 25.

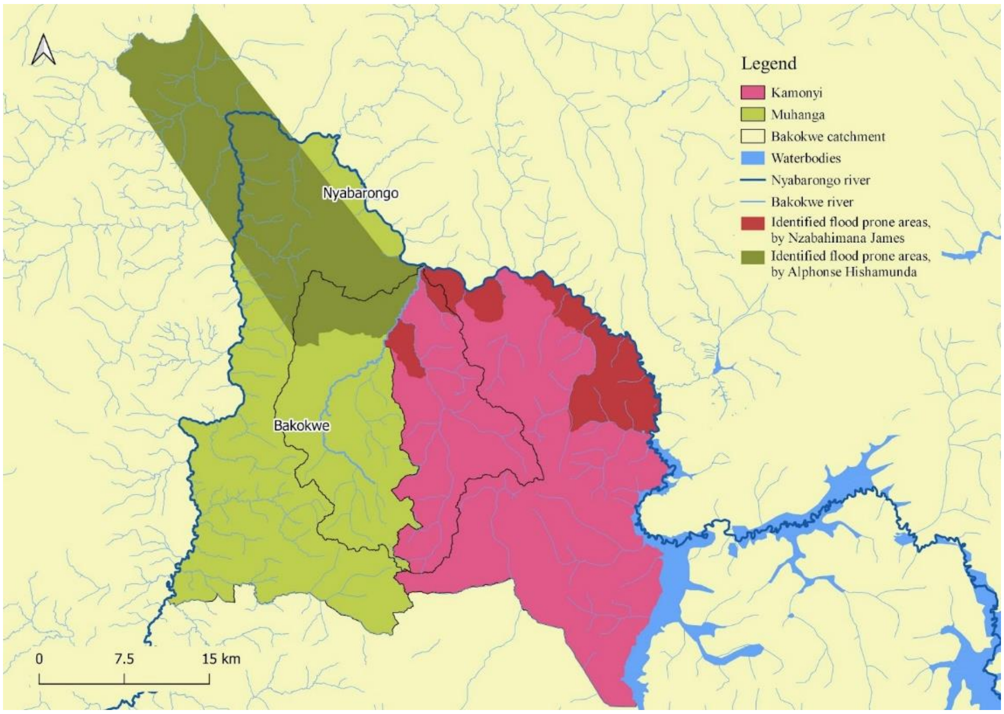


Figure 25. Identified flood prone areas by Nzabahimana (2022) and Hishamunda (2022).

Mr. Nzabahimana James, named Muyange cell in Kayumbu sector, Cubi and Kirwa cell in Kayenzi sector, Kabuga cell in Ngamba sector and Runda sector, all in Kamonyi district. Mr. Alphonse Hishamunda, named a corridor extending between Shyira, Vunga and Ndiza. These areas are all located in proximity to the Nyabarongo river, and a few of them in or close to the Bakokwe subcatchment.

The population density of the Bakokwe catchment is approximated to be 493 inhabitants/km^2, which globally is considered very dense (The World Bank Group, 2022) but in Rwanda it is close to the average population density. The population density is one of the factors that Mind'je et al. (2019) and Nahayo et al. (2019) among others consider when assessing the vulnerability to floods, since this affects the amount of people exposed to the consequences of floods. Another important factor, discussed by Mind'je et al. (2019) is how the perception of risk of a flood hazard is in the community. Bostrom (2012) showed that if a community already has experienced one hazard of a certain type, this community will be more prepared and thus less susceptible than a community that does not have a history of that hazard occurring. Thus, the more floods a community has experienced, the more likely it is that the community will be more prepared and less vulnerable.

The Bakokwe catchment have experienced flood events but the estimated severity and frequency varied in the catchment (data from MINEMA, 2021). According to the four respondents to the questionnaire, the main consequence of flooding in the Bakokwe subcatchment and the Nyabarongo catchment are loss of human lives, loss of livestock, loss of property (in one case specified as farms), loss of crop and agriculture production, destruction of infrastructure such as roads and water supply, deterioration of health conditions owing to waterborne diseases, pollution of water bodies and siltation of Nyabarongo and Bakokwe river by upstream erosion.

The desired solutions to implement in order to prevent damage caused by floods, according to the respondents of the questionnaire, include clearing of sediment from river floodplains, erosion control by constructing terraces, river bank and waterways protection. Other present solutions are gully rehabilitation, new rain water harvesting techniques, constructions of dams and retention ponds, plantation of trees, relocation of vulnerable households, as well as an awareness campaign to the population on the prevention of floods.

Susceptibility to erosion and landslides

Soil erosion is a threat to 55% of the land in the country, which has been proven by the high sediment load in rivers together with pollution from agricultural fertilisers, mining activities and industrial effluents (RWB, 2021). During the field visits, the total suspended solids were measured at nine of the locations to estimate the sediment load and soil erosion in the catchment. The results of these measurements are presented in Table 10.

Table 10. Measured TSS-concentrations in milligrams per litre at the measuring points on the 1st of March, ranked after observation-IDs. For location of the measurement point, see Figure10.

ID	1	3	4	5	7	8	9	10	11
TSS [mg/l]	402	964	19	271	545	656	3235	1735	4950

The results from Table 10 show that, as the Bakokwe river progressed, the TSS increased, and that the Nyabarongo river had a higher TSS-value than the Bakokwe river and its tributaries. The results also show that the Nyabugogo river (ID11), which is a tributary to the Nyabarongo river downstream of Bakokwe river, contributes with a high amount of sediment to the Nyabarongo river. These measurements confirm the studies of Kulimushi et al. (2021) and Karamage et al. (2016), who found that the Nyabarongo and its tributaries experience heavy sedimentation. The further downstream in the Bakokwe river that the measurements were taken, the higher were the TSS-levels, and similarly in the Nyabarongo river. The visibly clearest measurement point, ID4 in Mutumba river, had a significantly lower amount of TSS than the other rivers and served as a comparison to understand the high levels in the other water bodies. This location was observed to have grass covered fields and sparse forests around it, and no signs of erosion or mining activity could be seen. Thus, the results in Table 10 confirmed the observations during the field visits and indicated that erosion and mining activity results in high TSS-values. The respondents to the questionnaire all confirm these indications, as they agreed that the sediment load is high in the Bakokwe and Nyabarongo river due to the erosion and degraded watersheds and river systems.

The area of the upper Nyabarongo catchment that borders the Bakokwe subcatchment, shows high susceptibility to landslides according to the predictions of Nsengiyumva and Valentino (2020), and according to Karamage et al. (2016), the entire area of the Nyabarongo catchment face a high risk of soil erosion. The identified soil profiles in the Bakokwe subcatchment are presented in Figure 26, which show signs of erosion and soil loss.

Figure 26. Soil profiles in Bakokwe subcatchment on the 22nd of March 2022.

The steep slopes, deforestation and predominant agricultural land that Bakokwe is made up of (RWBa, 2022) together with the soil profiles (shown in Figure 26) and the sediment composition of the soil (Jones et al., 2014) all indicate that the Bakokwe subcatchment possibly have a high risk of erosion and landslides when experiencing heavy rainfall or high runoff. The overexploitation of soil and the extensive erosion that have taken place in the most parts of the Nyabarongo catchment have resulted in high amounts of soil being washed away into valleys, and as a result, extensive sedimentation of the main rivers in the catchment have occurred (Kwisanga, 2017). This is confirmed by the presented results in Table 10. The hilly mountains and steep slopes of the catchment, together with heavy rainfall, fragile soil, and high pressure of human activities in the catchment have led to that Nyabarongo catchment is very susceptible to soil erosion (Kulimushi et al., 2021). Kulimushi et al. (2021) assessed the erosion risk of several subcatchments in the Nyabarongo catchment, and the conclusion for Bakokwe subcatchment gave two different classifications, with one method classifying it as a low risk area for erosion and another method classifying it as a high risk area. This ambiguity indicates the difficulties in assessing the susceptibility to erosion of an area. Karamage et al. (2016) concluded that 96% of the soil loss in Nyabarongo catchment originates from cropland, and unplanned and illegal settlements will lead to even more severe erosion.

Disaster events and rainfall data

In order to understand the history of occurrence and impacts of heavy rainfall, floods and landslides in Bakokwe subcatchment, historically reported events in Rwanda and its consequences as well as historical precipitation patterns in Bakokwe catchment were assessed to confirm the occurrence and extent of such events.

When asking respondents of the questionnaire if there are any records on floods and landslides in the area, one respondent stated that records on floods are provided at sector level, more specifically damage to crops recorded by the district agronomist. The sectors located within the Bakokwe subcatchment were never contacted as it was considered to be too extensive work due to limited time and limited language skills. Mr. Nzabahimana James stated that there is no record of floods and their consequences in Kamonyi district while Mr. Alsaad Ndayizeye referred to MINEMA for information on floods and landslides. Mr. Alphonse Hishamunda stated that a joint assessment was conducted by different institutions and that a report was submitted to the Office of the Prime Minister for consideration but that it cannot be shared. The annual disaster reports from MINEMA were used and summaries and the results are presented in the following sections.

Reported natural disasters in Rwanda

The retrieved reports on natural disasters such as heavy rainfall, floods and landslides in Rwanda have been gathered from different sources, which each report on different geographical levels. Thus, the reported events are presented here on a national level, followed by reports on, and estimation of events in the Bakokwe catchment.

National level

A summary of MINEMA's published annual reports on the effects of natural disasters in Rwanda for 2016-2021 are presented in Figure 27-31 (data from MINEMA, 2021; Hishamunda, 2022). The consequences of loss of human lives, loss of livestock, loss of hectares of crop, damage to property, and damage to roads and bridges were analysed further.

No further information on the effects of natural disasters before 2016, or more precise causes within each district was available from MINEMA. No information was available on more exact location, dates, or duration of the natural disasters, or on how the categories of disaster or consequences were defined or whether the definitions changed between the years. Also, no information was available on how data was collected and confirmed. The reports on causes and consequences on a national level was used to estimate the number of effects in the Bakokwe catchment. Figure 27 presents the natural disasters causing loss of human lives in Rwanda for the years of 2016-2021.

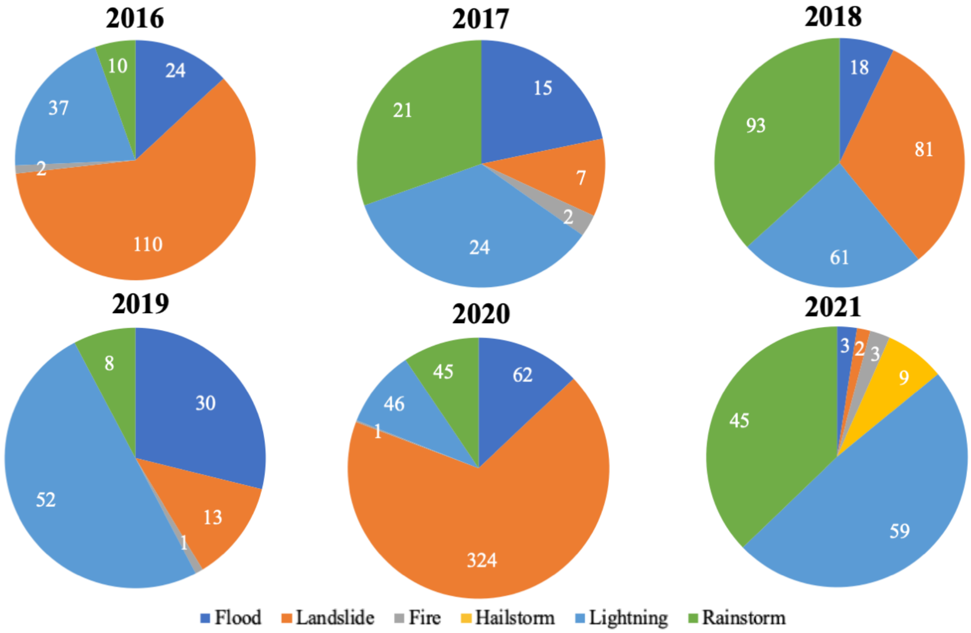


Figure 27. Natural disasters causing loss of lives in Rwanda between the years 2016 and 2021 (data from MINEMA, 2017-2021; Hishamunda, 2022). The numbers illustrated in white represent the number of lost lives.

Figure 27 shows that the main reported causes of loss of lives in Rwanda in 2016-2021 were lightning, landslides, rainstorms and floods. In 2019, floods were the second biggest cause of loss of lives while landslides caused a majority of deaths in 2016 and 2020. Based on what's presented in Figure 27, there is no clear correlation between what caused the losses of lives each year in Rwanda 2016-2021. Uncertainties on what data and how data was collected made it hard to further evaluate the causes. The proportions of reported natural disasters causing loss of livestock between 2016 and 2021 are presented in the following figure.

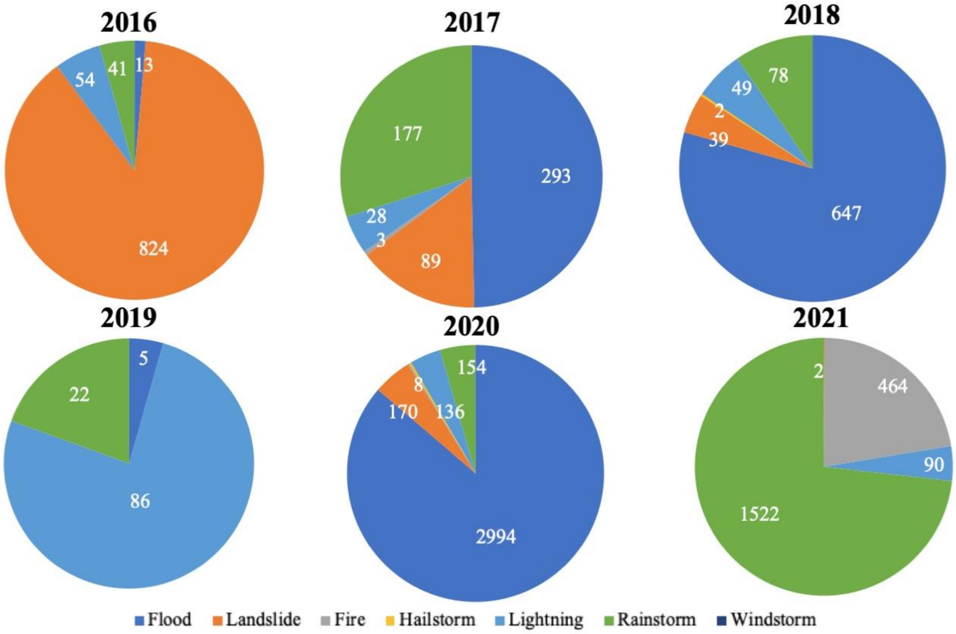


Figure 28. Natural disasters causing loss of livestock in Rwanda 2016-2021 (data from MINEMA, 2017-2021; Hishamunda, 2022). The numbers illustrated in white represent the number of reports of lost livestock.

The reported cause of lost livestock differed between the years and there was not one dominant disaster causing all lost livestock. Floods were reported as the dominant cause in 2017, 2018 and 2020, according to the figure. Landslides, lightning and rainstorms caused the majorities of loss of livestock in 2016, 2019 and 2021 respectively. Based on the results in Figure 28, no clear conclusion can be drawn on trends in disasters causing loss of livestock. For the number of hectares of lost and damaged crop for the earlier mentioned years, the proportions of the underlying causes are presented in Figure 29.

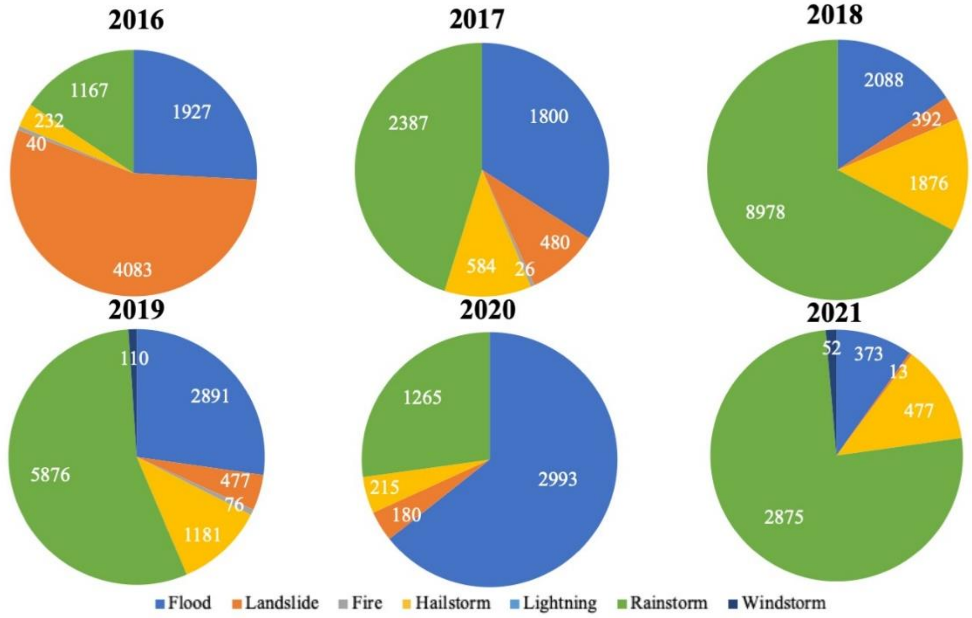


Figure 29. Natural disasters causing hectares of lost crop in Rwanda between the years 2016-2021. (data from MINEMA, 2017-2021; Hishamunda, 2022). The numbers illustrated in white represent the number of hectares of lost crop.

Rainstorms, floods, hailstorms and landslides were the main reported causes for loss of crop in the country. The results in Figure 29 follow more similar trends compared to earlier presented disasters, with floods and rainstorms reported as dominating causes. The number of reported landslides causing lost crop have decreased over the years, according to Figure 29. As the reported events by MINEMA does not specify geographical location of the disasters, it is highly likely that the effects on cropland differs in different parts of the country. The reported cause of damage to property in Rwanda for the years 2016-2021 are presented in Figure 30.

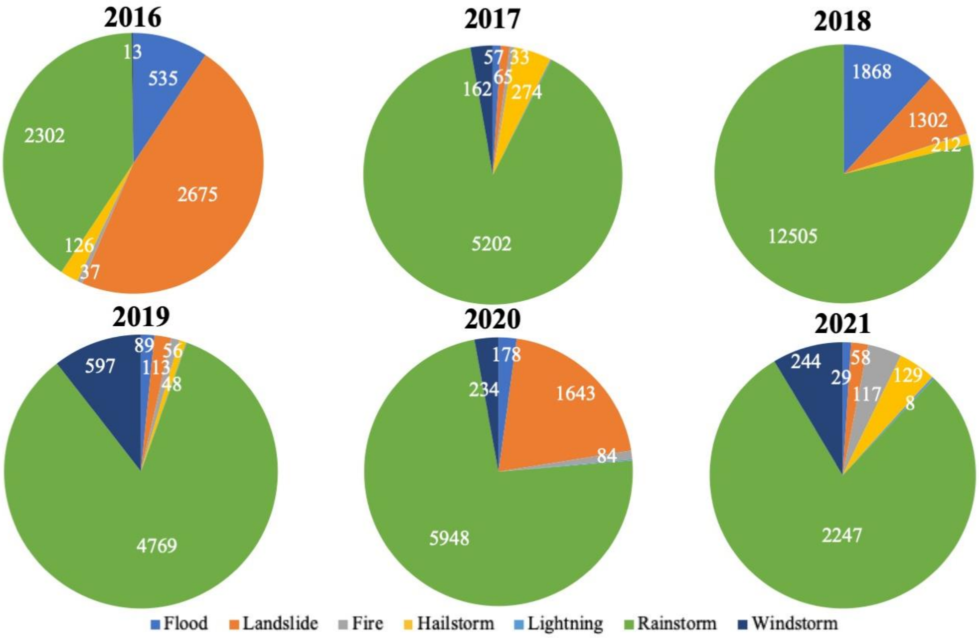


Figure 30. Natural disasters causing damage to property in Rwanda between the years 2016 and 2021 (data from MINEMA, 2017-2022; Hishamunda, 2022). The numbers illustrated in white represent the number of damaged property.

Rainstorms stood for a clear and dominating majority of the number of reported damaged properties in Rwanda between 2016 and 2021, hence is a possible threat to safe and secure properties. No other categories follow clear trends, but landslides, windstorms and floods were also affecting the number of damaged properties according to the reported events by MINEMA. Since no information was possible to retrieve on how and what damages was reported, and since the properties are not evenly distributed throughout the country, but rather centralised around villages and cities with unplanned settlements forming (Karamage et al., 2016), it is not possible to conclude if the results presented in Figure 30 are representative for a majority of the country. The proportions of natural disasters causing damage to roads and bridges are presented in Figure 31.

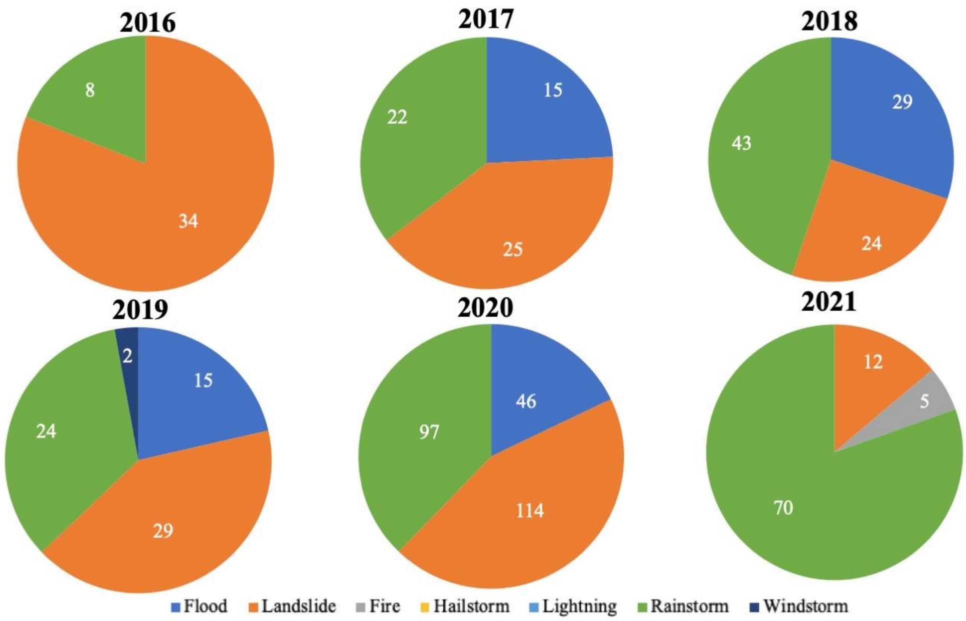


Figure 31. Natural disasters causing damage to roads and bridges in Rwanda between 2016-2021. (data from MINEMA, 2017-2022; Hishamunda, 2022). The numbers illustrated in white represent the number of damaged roads and bridges.

Landslides, floods and rainstorms have the largest negative effect on roads and bridges, and the years 2017-2020 show similar results. The results presented in figures 27-31 confirms rainstorms, floods and landslides as major causes of loss of lives, loss of livestock, loss of crop, damage to properties and damage to roads and bridges according to reports from MINEMA. But, the uncertainties in the reported data makes it hard to draw conclusions on more exact trends. The figures show that 2016 was a year where landslides were reported as causing a majority of the disaster while heavy rainstorms caused most disasters in 2021. To further confirm the distribution of consequences of flood, heavy rainstorm and landslide events, and the proportions of each consequence is presented for each year in Figure 32.

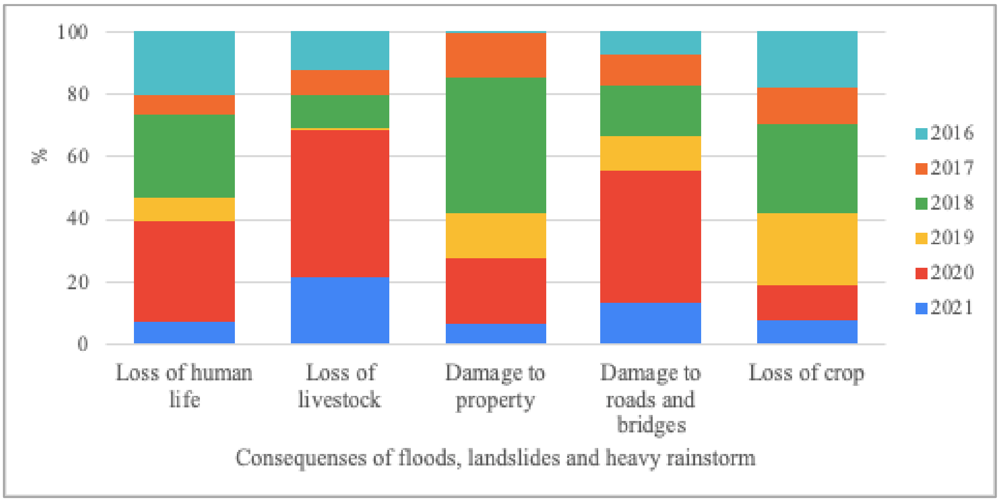


Figure 32. The proportions of reported impact cases in Rwanda due to floods, landslides and heavy rainstorms between 2016-2021. (data from MINEMA, 2017-2022; Hishamunda, 2022).

The distribution of reported consequences due to floods, landslides, and heavy rainstorms for 2016- 2021 in Rwanda are summarised in Figure 32. The figure shows that consequences within each category were reported each year, and that the reported deaths, loss of livestock, damage to roads and bridges was the highest in 2020, while 2018 was the year with the highest reported damaged properties in Rwanda.

The number of events of severe disasters related to heavy rainstorms, floods and landslides reported by BBC, New Times, ICRC, FEWS NET and The New Humanitarian are presented in Figure 33. The articles and reports of events were used to confirm consequences of floods and to confirm dates, locations and durations of such events. No further information was possible to retrieve from ICRC on how they distributed their efforts and monitored floods. The duration of reported events spanned between a few days and several months, and the geographical position varied from specific sectors to widespread parts of the country. The reported events with unspecified consequences, year or location were disregarded.

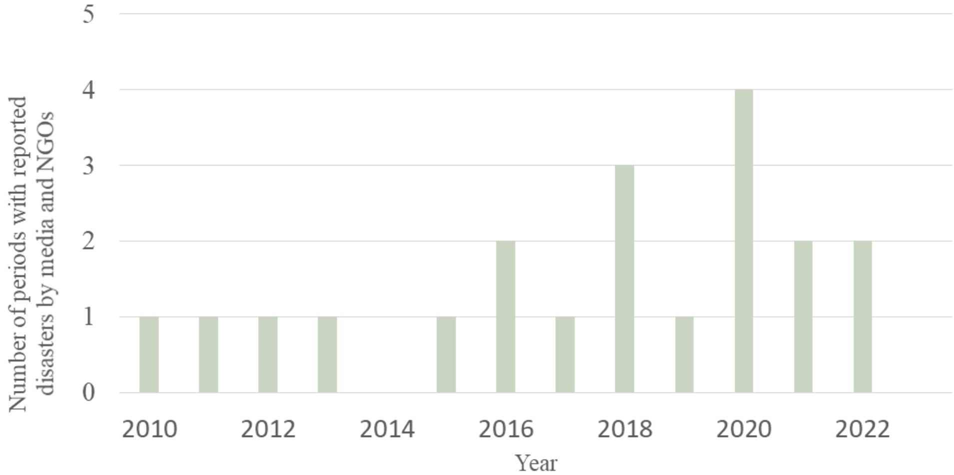


Figure 33. The number of reported periods of disaster related to floods, landslides and heavy rainstorms between the years 2010 and 2022. (data from BBC NEWS 2016 and 2018, Nkurunziza a,b,c, 2022, FEWS NET 2015,2016,2018 and 2020, and The New Humanitarian, 2012).

The number of reported events and periods of disasters from media sources and NGOs vary between 0 and 4 events yearly. Year 2020 had the highest number of reported disaster periods and the number of reported events were higher for 2016-2022 compared to 2010-2015. The yearly disaster reports by MINEMA (2022) indicates that the consequences of heavy rainstorms, floods and landslides are more severe, as what was reported by media and NGOs was limited and incomplete. The effects have also been further analysed for the Bakokwe catchment together with rainfall data for the corresponding years and the results are presented in the following section.

Bakokwe catchment

The annual reports from MINEMA do not specify location, time or duration of an event and no further or more detailed information was possible to retrieve regarding causes, location, time or duration of disaster events in the Bakokwe catchment. Therefore, estimations were made and corresponding rainfall data for the years of reported disaster events were analysed. The reported consequences for 2016-2021 in Muhanga and Kamonyi districts are presented in Appendix 2.1, and were used to estimate and calculate the losses and damages due to floods, heavy rainstorms, and landslides in Bakokwe catchment. The calculation are based on the following assumption:

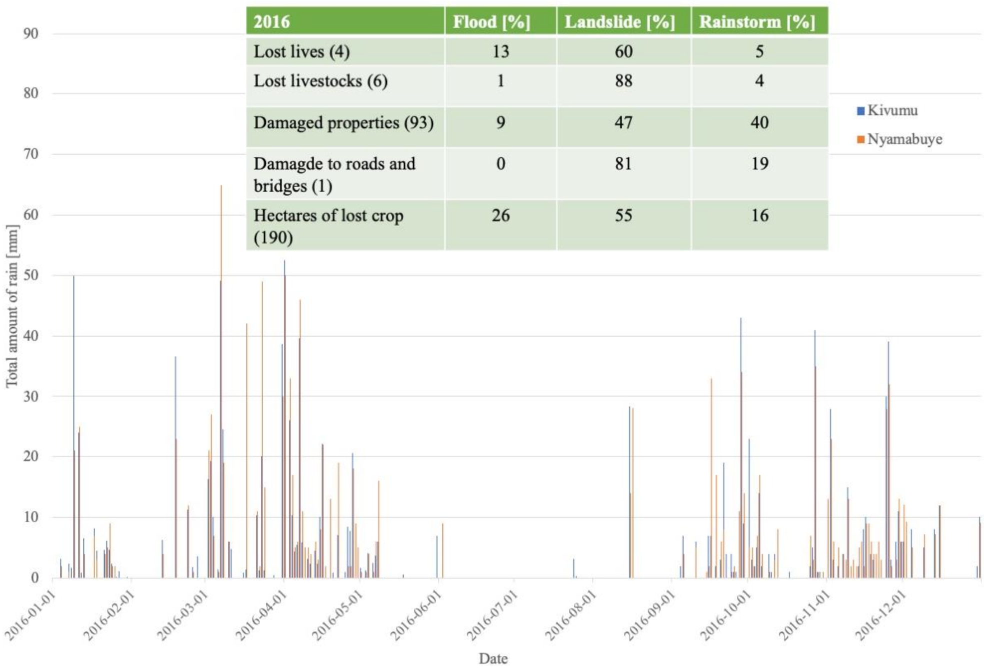
- Bakokwe catchment covers 29% of the total area of Muhanga and Kamonyi district and is evenly distributed between the two districts (Muhanga district, 2022; Kamonyi district, 2022).

- 29% of the total number of hectares of crop and livestock within Muhanga and Kamonyi district were situated within Bakokwe catchment between 2016-2021.

- 26% of the total population and number of properties within Muhanga and Kamonyi district lived and were located within Bakokwe catchment between 2016-2021.

- Roads and bridges were evenly distributed throughout the districts.

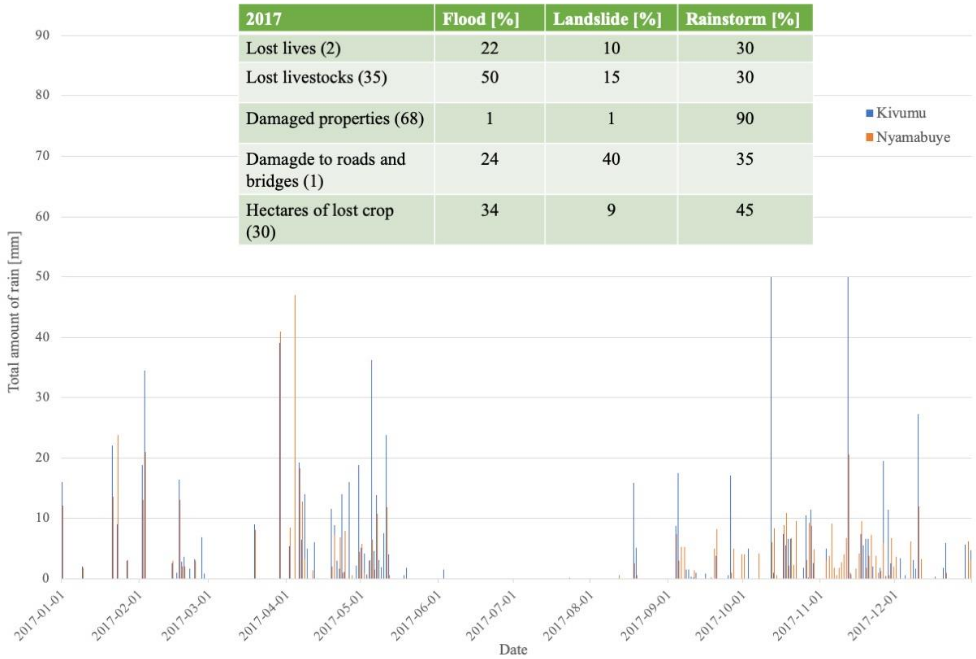
The daily rainfall data from the two meteorological stations located upstream in the Bakokwe catchment, Kivumu and Nyamabuye (see Figure 6), for the years 2016-2021 were plotted and presented together with the estimated number of disasters within the catchment for each year and with specific events reported by media or non-governmental organisations, in that case presented in yellow in the figures. The estimated disasters based on the data form MINEMA were not confirmed to have been caused by heavy rainfalls, floods or landslides, and the analysis was made to give hypothetical and possible approximations of time and duration, if the reported number of disasters were to have been affected by heavy rainfall. The results are presented in Figure 34-39.



2016	Flood [%]	Landslide [%]	Rainstorm [%]
Lost lives (4)	13	60	5
Lost livestocks (6)	1	88	4
Damaged properties (93)	9	47	40
Damagde to roads and bridges (1)	0	81	19
Hectares of lost crop (190)	26	55	16

Figure 34. Daily rainfall data from the two meteorological stations within Bakokwe catchment, Kivumu and Nyamabuye, in 2016 (METEO, 2019). The green table shows the estimated causes and consequences. The numbers in the parentheses present an estimated number of disasters in the catchment (data from MINEMA, 2017).

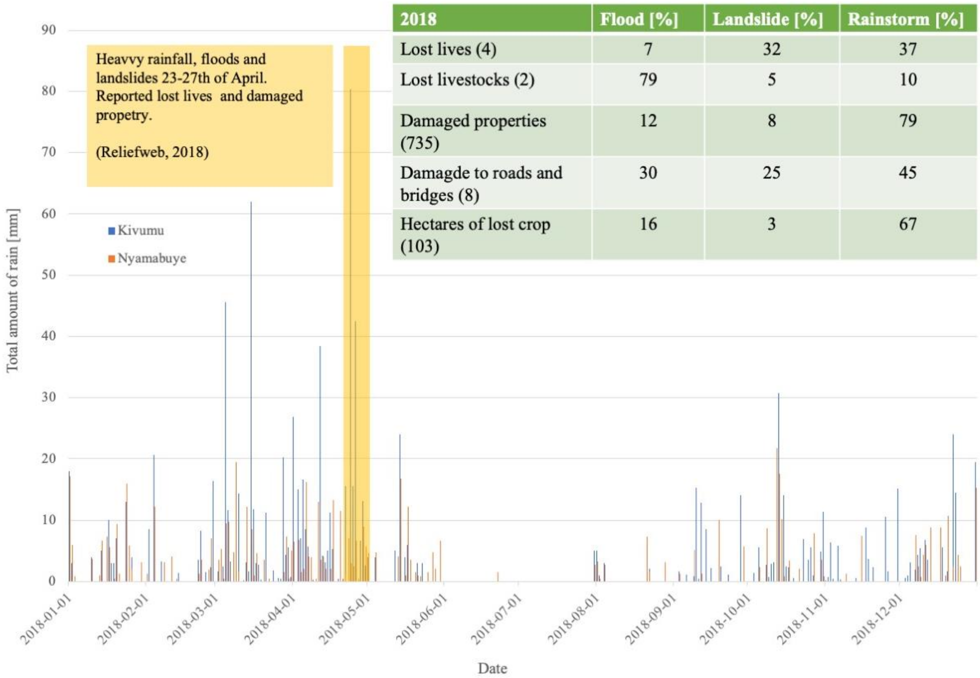
Figure 34 shows clear distributions of rainfall over the two distinguished rain periods, with several registered rains around 50 mm. The largest rains fell under the time of the year with the defined wettest rainy period. The two meteorological stations registered different amounts of rainfall and days of no rain scattered between large rains, indicating local and intense rainfalls with short durations. According to the estimation, the majority of the disasters were caused by landslides in 2016. The following figure presents the data for 2017.



2017	Flood [%]	Landslide [%]	Rainstorm [%]
Lost lives (2)	22	10	30
Lost livestocks (35)	50	15	30
Damaged properties (68)	1	1	90
Damagde to roads and bridges (1)	24	40	35
Hectares of lost crop (30)	34	9	45

Figure 35. Daily rainfall data from the two meteorological stations within Bakokwe catchment, Kivumu and Nyamabuye, in 2017 (METEO, 2019). The green table shows the estimated causes and consequences. The numbers in the parentheses present an estimated number of disasters in the catchment (data from MINEMA, 2018).

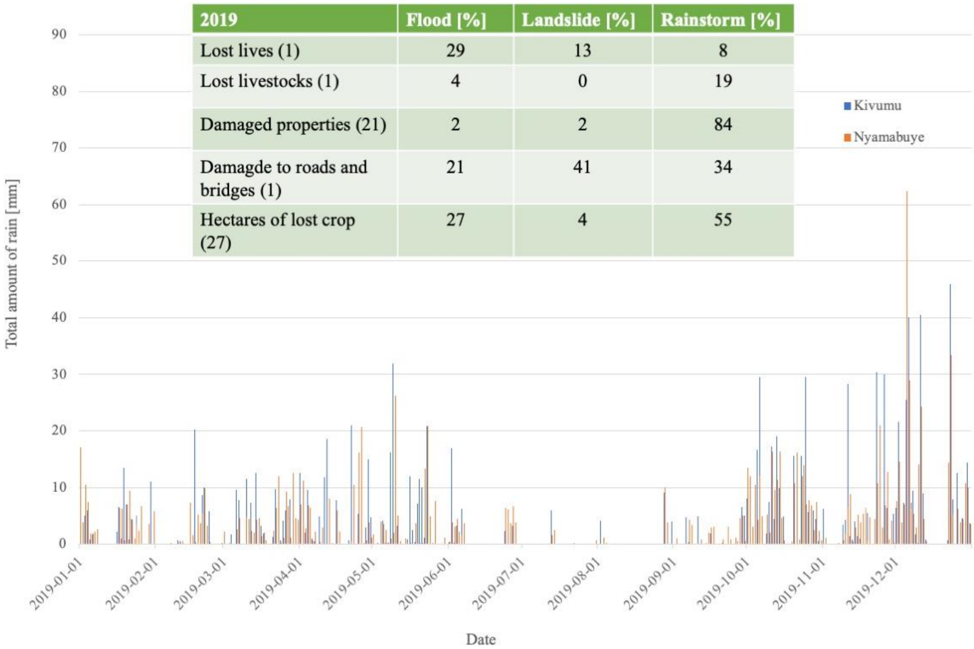
Figure 35 shows similar rain patterns for 2017 as for 2016 in Figure 34, but with fewer reported rain events in the first rain period. The largest rains registered in 2017 were smaller than the ones registered in 2016. More rains, with amounts above 50 mm, were registered in the late rain period, than the previous year. The estimated number of disasters were lower compared to 2016, with an exception of lost livestock, and a larger part of the disasters were estimated to have been caused by heavy rainstorms compared to 2016. Figure 36 presents the data for the following year.



2018	Flood [%]	Landslide [%]	Rainstorm [%]
Lost lives (4)	7	32	37
Lost livestocks (2)	79	5	10
Damaged properties (735)	12	8	79
Damagde to roads and bridges (8)	30	25	45
Hectares of lost crop (103)	16	3	67

Figure 36. Daily rainfall data from the two meteorological stations within Bakokwe catchment, Kivumu and Nyamabuye, in 2018 (METEO, 2019). The green table shows the estimated causes and consequences. The numbers in the parentheses present an estimated number of disasters in the catchment (data from MINEMA, 2020). The orange box represents the time period of a disaster event reported by Reliefweb (2018).

The time of the reported event by Relifweb (2018) coincided with the highest daily rainfall in 2018, a total reported rainfall amount of 80 mm on the 24th of April, registered by the Kivumu meteorological station. The rainfall event followed a period with a higher amount of rain, which previously was presented as just above normal amounts for this time period. In 2018, the estimated number of damaged properties was more than ten times the numbers in 2017. As most of the estimated number of lost lives and damaged properties are likely to have been caused by rainstorms, as seen in Figure 36, the periods of highest amounts of registered precipitation in March-May is likely to have been the period when most disaster occurred. With the same reasoning, rain amounts in the same range as the event on the 23rd-27th of April any other year would possibly have caused consequences in the same magnitude any other year as the ones reported in 2018.



2019	Flood [%]	Landslide [%]	Rainstorm [%]
Lost lives (1)	29	13	8
Lost livestocks (1)	4	0	19
Damaged properties (21)	2	2	84
Damagde to roads and bridges (1)	21	41	34
Hectares of lost crop (27)	27	4	55

Figure 37. Daily rainfall data from the two meteorological stations within Bakokwe catchment, Kivumu and Nyamabuye, in 2019 (METEO, 2019). The green table shows the estimated causes and consequences. The numbers in the parentheses present an estimated number of disasters in the catchment (data from MINEMA, 2020).

The largest reported rains fell in late 2019, at the end of the late rain period, with peak values of over 60 mm, at the Nyamabuye meteorological station. The beginning of the year was less wet than other years, correlating to a lower number of estimated consequences in 2019 compared to the other years. Figure 38 presentes the the data for 2020.

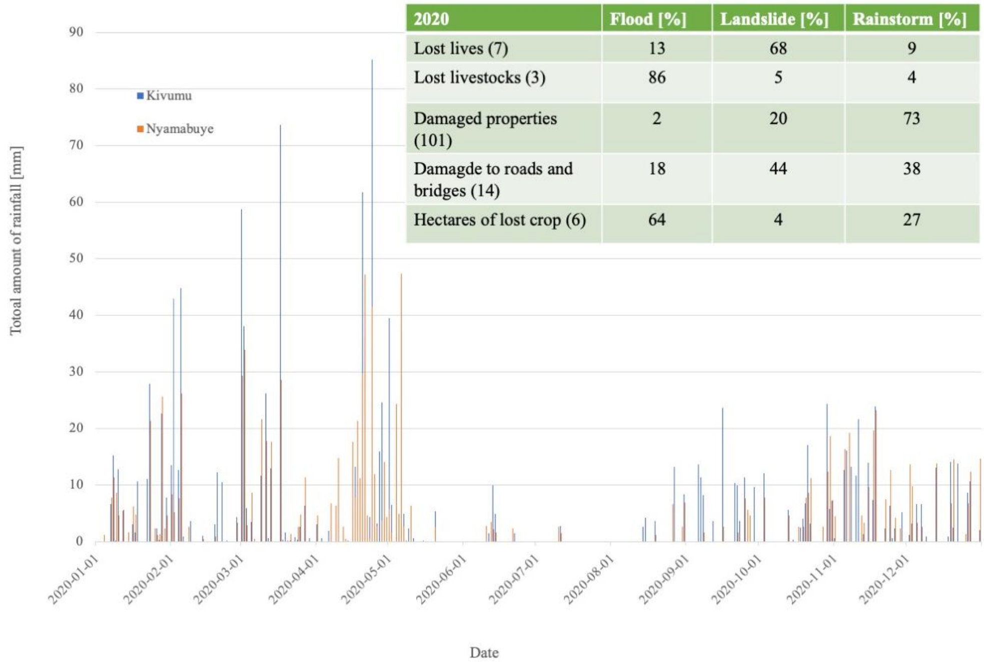


Figure 38. Daily rainfall data from the two meteorological stations within Bakokwe catchment, Kivumu and Nyamabuye, in 2020 (METEO, 2022). The green table shows the estimated causes and consequences. The numbers in the parentheses present an estimated number of disasters in the catchment (data from MINEMA, 2021).

For the period between the 16th of April and 7th of May, both meteorological stations registered rain almost every day and Kivumu registered rain amounts of above 80 mm on the 24th of April, the same rainfall amount as registered in 2018. The latter rain period gave less rain amounts in 2020. As 7 lost lives were estimated in Bakokwe catchment in 2020, and as most of them possibly were caused by landslides, the heavy rainfalls registered in April and May might have been some of the causing events, as heavy rainfall can induce landslides. Also, most of the estimated number of damaged properties were damaged by rainstorms, and the period of April-May is likely to have been the time for a large part of the disasters. No consequences were reported by the media or NGOs, despite the intensive rainfalls. The following figure shows the results for 2021.

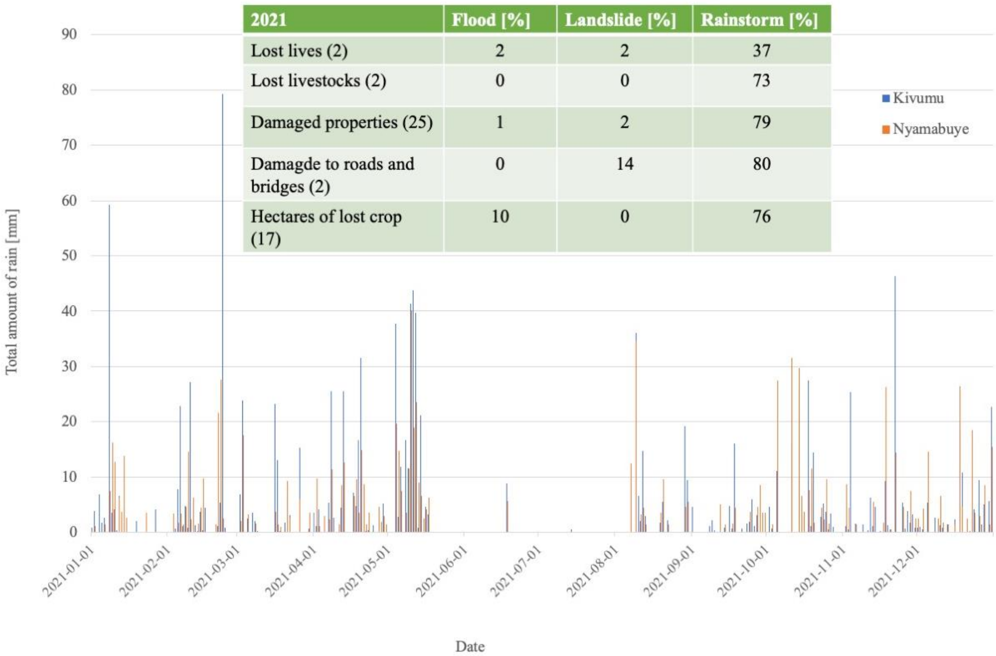


Figure 39. Daily rainfall data from the two meteorological stations within Bakokwe catchment, Kivumu and Nyamabuye, in 2021 (METEO, 2022). The green table shows the estimated causes and consequences. The numbers in the parentheses present an estimated number of disasters in the catchment (data from Hishamunda, 2022).

The registered rainfall in 2021 was more evenly distributed throughout the two rain periods compared to 2020 (figure 38). One rain event of the same magnitude as the one registered 23rd-27th of April 2018 (see Figure 38) fell on 23rd of February, reported by the same meteorological station. No disaster was reported by media or non-governmental organisations at that time, and fewer disaster consequences were estimated for 2021 compared to 2018, thus a clear majority of the disaster were estimated to have been caused by heavy rainstorms in 2021. If the reported event happening in 2018 were to represent how the disaster events were distributed over the year, most of them would have occurred at the time of the two rain periods, giving approximately 70% of the annual rainfall (Siebert et al., 2019).

The estimations made in Figure 34-39 all indicate that rainstorms, floods and landslides have had effects on humans, livestock's, crops, properties and roads and bridges in Rwanda. The results also indicate that the number of disasters have been under reported. To further confirm the effects, the reported events by media and non-governmental organisations in Kamonyi and Muhanga.

The retrieved reported events in the Muhanga and Kamonyi districts were assumed to have happened within the Bakokwe catchment. To be able to assess and identify any possible direct response and effect of heavy rain, the available rainfall data was assessed for the time of the reported disasters. The rain data from the rain gauges or the ARC2 database within the district was normalised for one week prior to the event up to, and including, the date of the event. This was done to assess and differentiate flash floods from riverine floods and to determine if the amount of rainfall was normal or not. A comparison with how the rainfall deviates from normal was done with the results of the field visit, in order to estimate the discharge of the Bakokwe river in the downstream part.

Heavy rainfall in Muhanga district, start of January to 26th of March 2010

From the beginning of January 2010, up to the 26th of March 2010, heavy rains were reported in the south, west and north provinces. One of the districts affected was the Muhanga district, where the heavy rain caused flooding and landslides. The consequences following the reported heavy rains were, on the 26th of March, loss of human lives, human injuries, loss of crop, damage to properties and damage to roads and bridges. (Reliefweb, 2010). The normalised mean daily rainfall over the catchment during the event, first of February to last of March 2010, is presented in Figure 40.

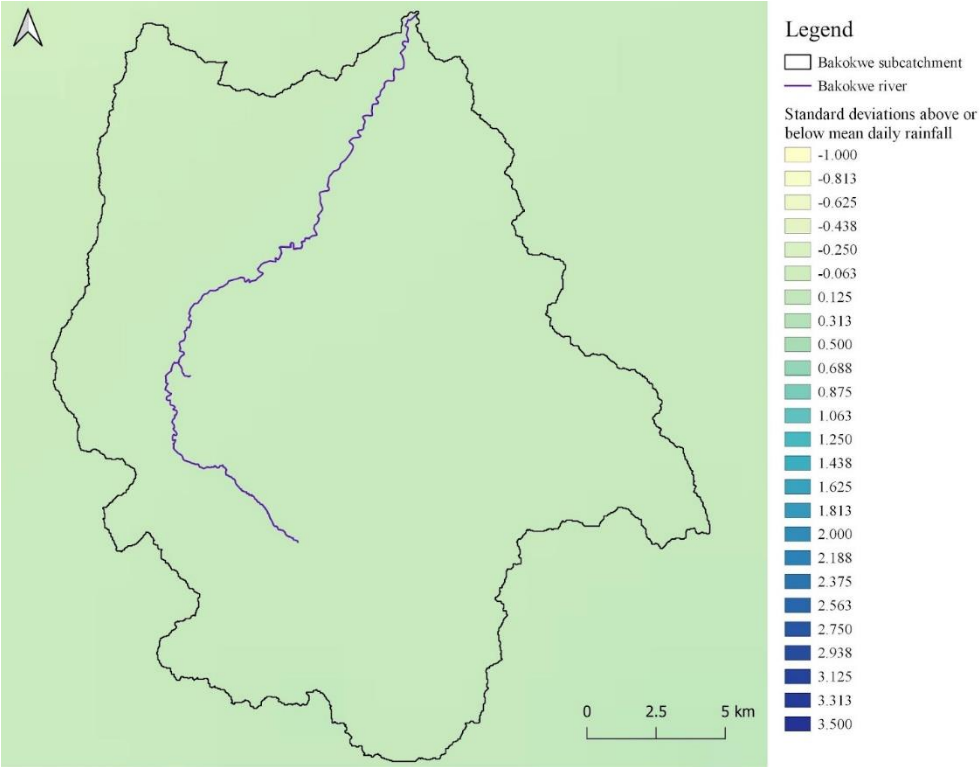


Figure 40. The normalised, average daily rainfall over Bakokwe catchment between the first of January and the last of March 2010. Normalised on data from 1983 and forward, (data from METEO, 2019).

From the result presented in Figure 40, it can be seen that the average daily rainfall over Bakokwe between January and March 2010 does not exceed normal rainfall to any great extent. In some areas upstream of the catchment, the rainfall was around 0.2 standard deviations above normal and in some parts in the downstream areas of the catchment the rainfall was below normal. Comparing this deviation to the results of the field visit, the discharge of the Bakokwe river in the most downstream part should be around 10 m^3/s which was the lowest flow estimated during the field visit. Several possible conclusions can be drawn based on these observations. Possibly, other factors rather than the rainfall were contributing to the reported damages, such as riverine flooding and a high water load under a long period of time. However, the report states that heavy rainfall was observed and that it was what caused the damages, thus it might be normal that floods occur during this time of the year as the amount of rainfall is around normal. If that is the case, the number of reported disasters would be underreported at this time of the year.

Heavy rainfall in Kamonyi district, 23d to 27th of April 2018

On the 27th of April 2018, heavy rainfall was reported to have affected several districts in the central and north-eastern parts of Rwanda for several days. This induced landslides and floods, of which 24 people died. No reports on where these people were situated within the district. In Kamonyi district injured structures and buildings were reported (Reliefweb, 2018). When these injuries and situation were reported, it was predicted that more heavy rainfall and thunderstorms were to follow but no reports on damages in the following months was found. The normalised daily mean rainfall during the week leading up to the event are presented in Figure 41.

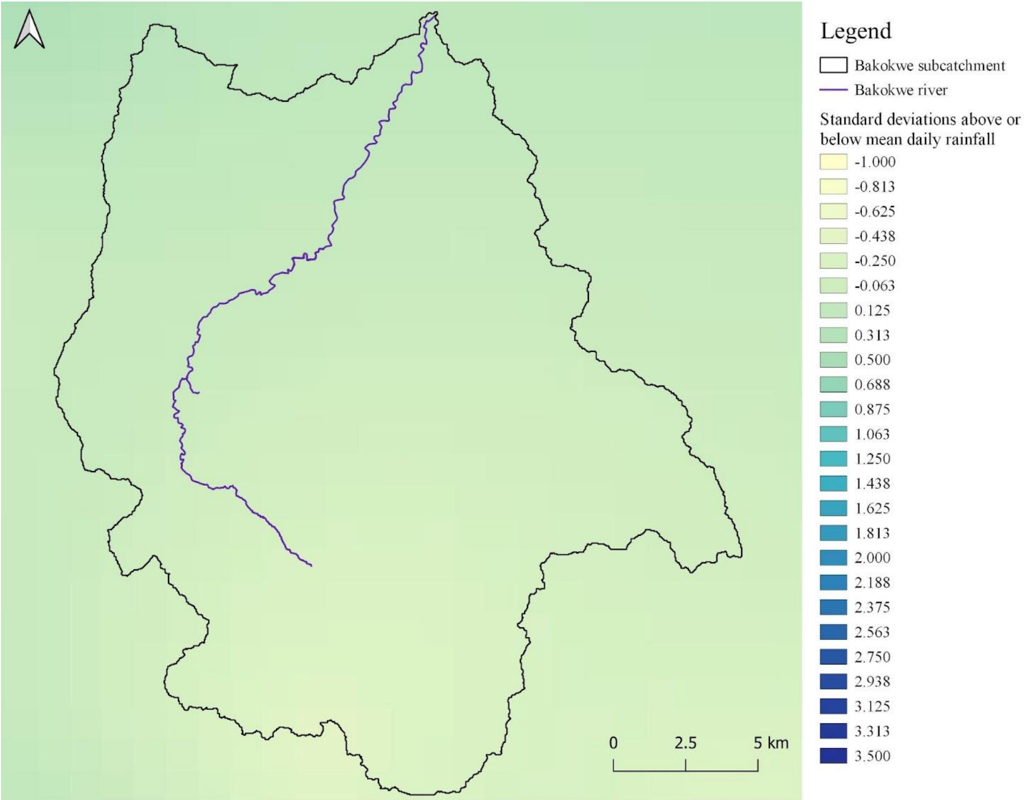


Figure 41. The normalised, average daily rainfall over Bakokwe catchment between the 16th and the 27th of April 2018. Normalised on data from 1983 and forward, (data from METEO 2019).

The normalised rainfall in Figure 41 indicates that the rainfall was a bit higher than normal in the downstream parts of the Bakokwe catchment, i.e. the northern parts and in the upstream areas the rainfall was a bit lower than normal with about 0.3 standard deviations below normal mean values. In the western parts, the rainfall was higher than normal with between 0.1 and 0.5 standard deviations. These levels of rainfall drains down in the Bakokwe catchment and are comparable to the observations on the 16th of April 2022 in the Bakokwe catchment, which indicates that the discharge of the river should be around $10m^3/s$. As the levels of rainfall is low upstream in the Bakokwe catchment, but high in the downstream parts, it is likely that there were little to no riverine flooding in the Bakokwe river but rather flash floods closest to the boundaries of the subcatchment, and on the other hand, the areas around the Nyabarongo river on the northern borders of the Bakokwe catchment are likely to have experienced riverine flooding. However, this rainfall event is close to normal levels of precipitation which indicates that similar events may take place at this time of the year.

Heavy rainfall in Muhanga district, January to February 2022

During the two first months of 2022, heavy rainfall was predicted by the METEO of Rwanda which came true to some extent. In January alone, 15 people died and 37 were severely injured by floods, landslides, thunderstorms, rain- and windstorms (Nkurunziza a, 2022). A reported rain event in February damaged and destroyed several bridges and roads in the district of Muhanga (Nkurunziza b. 2022). In Figure 42, the normalised daily mean rainfall during these months in the Bakokwe catchment are shown.

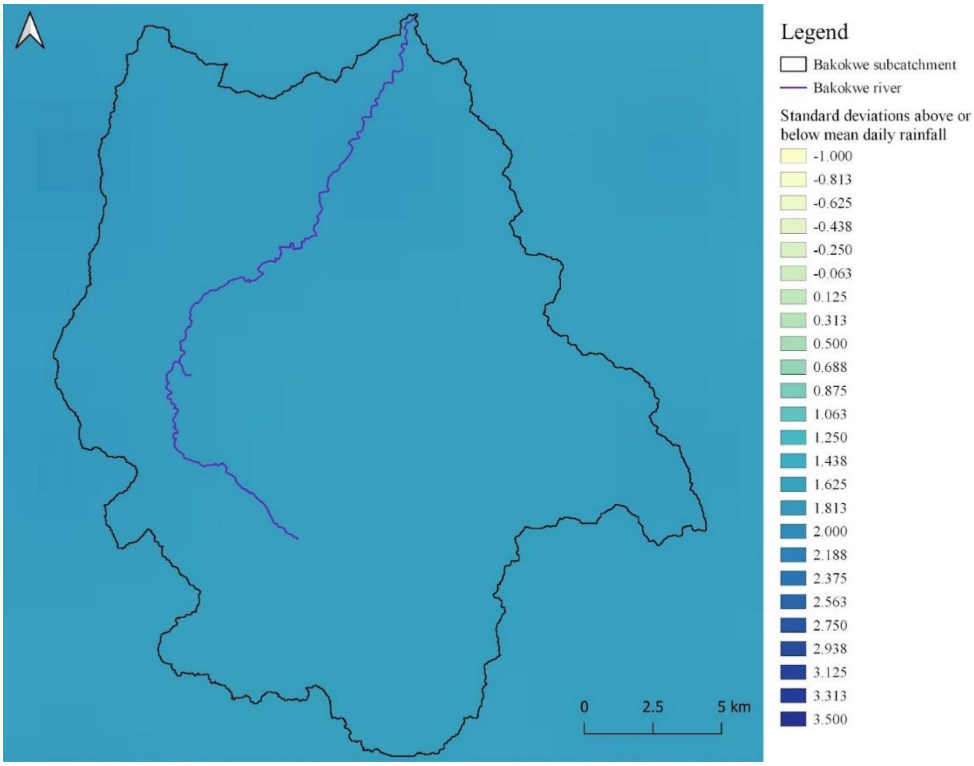


Figure 42. The normalised, average daily rainfall over Bakokwe catchment between the first of January and the last of February 2022. Normalised on data from 1983 and forward, data from ARC2.

During January and February 2022, the precipitation was above normal levels over the catchment which can be seen in Figure 42. According to the results, the eastern parts of the Bakokwe subcatchment had rainfalls between 1.5 and 2 standard deviations above normal, whilst in the upstream and western areas of the catchment the rainfall was between 1.3 and 1.5 standard deviations above normal. This validates the predictions made by the METEO and indicates that the reported damage was not normal for this time of the year, but a consequence of abnormal heavy rainfall. However, the results are based on satellite data with uncertain quality. The high rainfall above normal presented in Figure 42 might therefore not be representative for the event. As this event took place in the time span of the field visits, the flow of the Bakokwe river can be estimated to be between 20 and 30 m^3/s, as were the estimated flows when the rainfall showed the normality it does in Figure 42.

Discussion

The aim of this thesis was to evaluate the causes, consequences and future challenges of floods and landslides in the Bakokwe catchment. The following sections summarise and discuss the main finding.

Causes

The main causes of floods and landslides in the Bakokwe catchment are heavy rainfall together with land cover changes, high population density, and the varied topography of the area. Between 2016 and 2021, the occurrence of floods, landslides and heavy rainfall that had devastating consequences showed no trend in the number of reported events. Due to a lack of information on how the data on causes was collected and how the categories were defined by MINEMA, it is uncertain whether the definitions changed over this period. A hypothetical explanation of the notable difference in national natural disaster causes for 2020 and 2021 could be a change in how flash floods were categorised, as floods in 2020 and heavy rainstorms in 2021. The data on causes from MINEMA was reported on a national level, and to try to understand the occurrence in Bakokwe subcatchment, the national data was applied on the catchment based on population density and the area of the catchment. It is not certain that this assumption is applicable to the extent that it was used, but no other way of retrieving this type of data for the Bakokwe catchment was found.

The precipitation data for 2016 and 2021 show that heavy rainfall fell during the two rainy seasons and little to no rainfall during the dry period in June to August. This implies that the Bakokwe subcatchment experience intense rainfalls every year during the rainy seasons which could result in floods and landslides. The events reported from the International Red Cross, FEWS NET, and media reports, included three events of heavy rainfall, floods, and landslides in Bakokwe that had severe consequences. However, the precipitation leading up to these events were normal, which implies that similar or more intense hydrological events most likely occur more frequently than the reports indicate.

The quality of the satellite rainfall data did not agree well with the observed data at the rain gauges in the Nyabarongo catchment for 1983 to 2021. The satellite data was used to evaluate the rainfall leading up to the reported disaster events and the field visits in 2022. Due to the low accuracy of the satellite data, the result of the normalised precipitation prior to the events of 2022 should not be considered reliable. However, the results indicate that the precipitation during the period before the events in 2022 was higher than normal compared to the historical satellite data. As the normalisation is performed on the satellite images, this still gives some indication that the reported events of 2022 were uncommon. On the other hand, normalised precipitation from the meteorological stations instead indicates that the rainfall leading up to the reported events prior to 2022 was close to normal. This makes it likely that similar disastrous events have occurred more frequently than the reports show. The rainfall data retrieved from METEO are probably more reliable than the satellite data, which are limited by their resolution, cloud cover, and approximate calculations of rainfall. However, there are big gaps in data from many stations between 1994 and 2010 as a consequence of the country's history as well as several shorter periods of no data during all years, which decrease the reliability of the data. Furthermore, there are only two stations located in the Bakokwe subcatchment and both are in the most upstream parts of the catchment which add uncertainty to the estimates of precipitation in the lower parts of the catchment. These different indications of the rainfall intensities and thus also of floods and landslides might have two explanations. Either, the precipitation of 2022 was extreme or the satellite data is not reliable.

Over the last thirty years, the land cover in the Bakokwe subcatchment have changed significantly from more extensive forest cover of 16% to almost no forest cover of 6% in 2021, giving place for agricultural land as well as settlements. The changes of land cover from 1990 to 2021 of the catchment was examined through a literature review and analyses of satellite images. The land cover of 2022 was also assessed during the field studies. The results of the field visits validated the land cover maps of 2021. Satellite imagery has several limitations when used to determine land cover, as the reflectance curves of vegetation of agricultural land is similar to that of natural open fields. The reflectance of impervious cover and water is also similar, which explains why the land cover between 2017 and 2021 from ESRI indicated much more settlements than the land cover of 2020, retrieved from the analysis performed on satellite imagery, which instead had significantly higher amounts of water. The use of different sources increases the reliability of the result, as it will limit the impact of the different sources of error in the analysis. However, the results of the land cover changes give a clear indication that the area has experienced severe deforestation since 1990, which has given place to agricultural land. Land covered by crops have higher susceptibility to erosion and this change in land cover will thus have increased the susceptibility to landslides. The increase of settlements have also increased surface runoff and the likelihood of flash floods.

A denser population increases the susceptibility to floods and landslides as even the unsuitable land must be used for housing and farming. The population density in Bakokwe catchment is similar to the average density of the whole country based on the projection of the population in 2020 from the census of 2012. The country had a population of about 13 million in 2020, and the projection based on the 2012 census estimated the population to be 12.7 million in 2020. Thus the projection can be deemed accurate enough. No data was found on the population census on sector level more recent than 2012. It would have been interesting to know how the COVID-19 pandemic affected the population in different areas of the country, however this data was not possible to retrieve covering the sectors of Muhanga and Kamonyi and thus it was not possible to calculate the population of the sectors in Bakokwe catchment. However, the projection made in 2012 indicates a rapidly growing population and the up to date values of population on national level show that the projected population increase from 2012 was accurate, even though more lives have been lost between 2020 and 2022 than expected.

Bakokwe catchment have high susceptibility to both floods and landslides, both due to the land cover and population density, but also due to the topography and geomorphology of the area. The area is hilly, just as large parts of the country are, and have soil consisting of sediment that are prone to erosion. The fact that these characteristics are similar to big parts of the Nyabarongo catchment and the country validates the assumption that the situation of the Bakokwe subcatchment is similar to many subcatchments of the Nyabarongo catchment. However, to further understand a potential relation between the flood and landslide risk of similar catchments, every catchment should be assessed individually, and more data on land cover change, reported events of floods and landslides, and rainfall is required.

Consequences

The presented consequences of heavy rainfalls, floods and landslides in Rwanda is mainly based on data from the MINEMA and their annual disaster reports. No disaster reports or data were published by MINEMA on events prior to 2016, and the only retrieved historical data to compare with was that between 1990 and 2015, when 82 000 people in Rwanda were affected by floods of which 183 lost their lives, with a calculated average of 7 lost lives per year. However, these numbers do not specify the consequences or the distribution between the years and must be seen as a weak indication, thus confirming the lack of historical data on consequences of heavy rainfall, floods and landslides. The consequences reported by MINEMA between 2016-2021 showed that people, animals, cropland, and infrastructure were affected and lost due to heavy rainfalls, floods and landslides, which was also confirmed by all respondents of the questionnaire. It is important to consider that the answer rate of the questionnaire was low, as only four out of ten of the distributed questionnaires was answered. The questions might not have been covering all aspects of the defined problem.

It was not possible to find out how the selection of events that were reported by MINEMA was made, since no information on location, dates, or duration of the natural disasters, or on how the categories of disasters or consequences were defined, was available. Also, no information was found on if the definitions changed between the years or on how data was collected and validated. Therefore, only estimations could be made on impacts for the Bakokwe catchment, which were based on data on national level and on general assumption. For instance, no account was taken of topography, geomorphology, or geographical position of the area when the national data was used for estimation for Bakokwe catchment. As the landscape differs throughout the country, the estimations might not have been representative. But if the actual number of disasters was in the range of the estimated values, it is likely that heavy rainfalls, floods and landslides also had large economic consequences in Bakokwe, as the result showed an estimate of 340 hectares of lost crop in Bakokwe catchment, with a total area of about 37 000 hectares, between 2016-2021, and agriculture was pointed out as one of the key features for the country's socioeconomic development.

Several meetings and contacts with the ministry responsible for the reporting of disasters, MINEMA, did not give any further information than in the reports. Limiting time and language skills made it impractical to try to retrieve more detailed information on sector level, which was suggested by Environmental & Social Safeguards Specialist at Muhanga District. This could possibly have filled the gaps of lacking information and data for both Bakokwe catchment and the country as a whole. With only six years of available data from MINEMA on impacts of heavy rainfalls, floods and landslides, it was not possible to identify any historical patterns or changes in this data for Bakokwe catchment.

Disaster events reported by the New Times, BBC, The New Humanitarian, ICRC, and FEWS NET were analysed from 2000. The ICRC reports were the most extensive, but no further information was found on the data collection process behind these reports. As impacts were reported on district levels, reports for the two districts covering Bakokwe, Muhanga and Kamonyi districts, were assumed to have happened in the Bakokwe catchment. Only a few of the reported events occurred in the Bakokwe catchment in the last 22 years, in 2010, 2018 and 2022. The rainfall during the events in 2010 and 2018 were both considered around normal, which indicates that floods, landslides and their consequences are underreported. According to estimates made on the data from MINEMA, there were losses or damages in Bakokwe every year between 2016 and 2021 to lives, livestock, and hectares of crops, properties, roads and bridges.

Interviews with the population in the Bakokwe area, as well as photos from the field sites, confirmed that high water levels, floods, and landslides are a problem in the area. This, together with the finding that there were normal rainfall periods during several of the reported disasters events indicates that consequences of heavy rainfalls are underreported by both media, NGO, and government institutions. As it was not possible to access news in Kinyarwanda due to lacking language skills, the range of references was limited. With more time, more effort could have been put into trying to access news in Kinyarwanda and perhaps widen the range of information and references.

Future challenges

The ambitious strategies and plans set up on national and regional level are pointing out agriculture as one of the key features for Rwanda's socioeconomic development, both for the majority of the Rwandan population and the population living within Bakokwe catchment. With the high reliance on local agricultural production, national and regional plans have been developed to decrease the vulnerability of the sector. But, the plans do not specify or develop guidelines for impacts of heavy rainfall, floods, or landslides. General challenges with plans and strategies can be uncertainties and difficulties of implementation, which these plans and strategies analysed do not discuss to any great extent.

The outlooks on impacts of heavy rainfalls, floods, and landslides on agriculture are also predicted to depend on the expected population growth and future livelihoods and land use, as plans of transformation of the rural areas are a key for social and economic development. As the population of Rwanda is expected to double by 2050, land consolidation will be promoted according to regional plans as a way of phasing out scattered farms and expanding commercial agricultural production to increase production. Housing and infrastructure are also expected to develop and a densification of areas such as Muhanga and Kamonyi districts is expected. With this comes further land cover change, as the demand on food production and housing increases. In addition, urban growth leads to an increase in impermeable surface, with more surface runoff and a higher need for storm water solutions. The population densities will likely increase in cities, as they are more and more urbanised. Hence, the number of people, livestock, hectares of crop, properties, and infrastructure that are exposed to floods and landslides will also increase. Based on present conditions and lack of data in catchments of the size of Bakokwe, there is still much to do to implement the ambitious plans and strategies and limit the consequences of heavy rainfalls, floods and landslides.

Additionally, climate change is projected to increase the occurrence and impacts of floods and landslides as well as the predictability of the seasons. The results of the IPCC report 2022 indicate that the extreme hydrological variability will be more intense as well as more frequent with time, but that yearly precipitation will stay approximately the same even. The studies considering Africa suffer from lack of data with the result of different models disagreeing on projections for the same basin (IPCCb, 2022). Nevertheless, it can be concluded that the extreme hydrological variability will get amplified with time (IPCCb, 2022) and that anthropogenic land use changes and climate change is certain to exacerbate intensity, frequency and spatial extent of floods and droughts throughout the world (IPCCa, 2022). As most of the agricultural practices in Africa (IPCCb, 2022), and Rwanda (Mikova et al., 2015), are rain fed, this increase in variability and uncertainty in occurrence and intensity of rainfall will risk affecting the agricultural harvest (IPCCb, 2022). It could also be seen that land suitable for tea and coffee plantations will decrease significantly (IPCCb, 2022). This will affect Rwanda as its economy is dependent on export of these goods. An indication of historical rain patterns in the Bakokwe catchment is shown in Figure 43, where reported total monthly rainfall data for within Bakokwe catchment are plotted on a time axis.

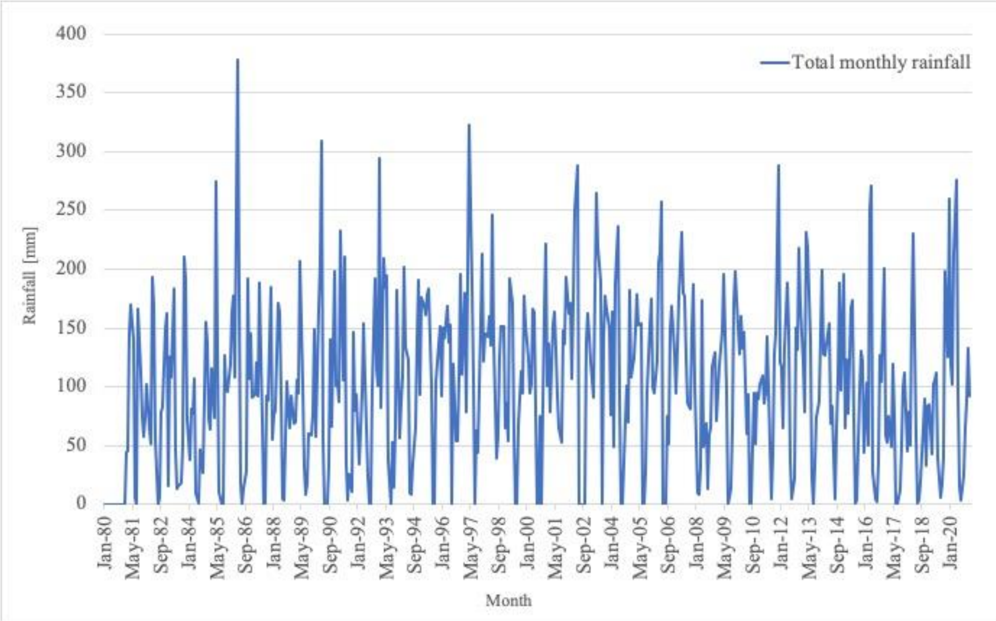


Figure 43. The total monthly rainfall reported in the Bakokwe catchment between 1980-2020. (data from METEO, 2019 and 2022).

Figure 43 shows some months with higher peak values, but does not show any clear trends or changes in total monthly rainfall in this area, which indicates that the monthly and yearly rainfall might have been approximately the same for this period. However, the intensity of single rain events are not shown in the figure and no conclusion can be drawn regarding the intensity or duration. The climatic variability and irregularity of rainfall have been shown to highly affect the population of Rwanda that depends on agriculture for a living (Mikova et al., 2015). Climate change will alter the precipitation and temperature pattern of Rwanda (IPCCb, 2022; Mikova et al., 2015; Nahayo et al., 2019), thus affecting the agricultural based population of Rwanda.

The variability and changes in soil moisture with geographical location indicates that the consequences are more complex and more difficult to predict (IPCCa, 2022). The results of the climatic projections of the IPCC does not enable unambiguous interpretations or recommendations but rather indicates that measures should be taken to minimise society's susceptibility to climatic hazards. The projections are made for tropical areas in general, and are thus not specific to Rwanda. As areas with rain fed agriculture are more vulnerable to changes in the hydrological cycle, the Bakokwe catchment and large parts of Rwanda will require measures to ensure stable food and crop production. Anthropogenic land use changes in the Bakokwe catchment will enhance the intensity, frequency and spatial extent of floods which further emphasise the need of rapid measures, to ensure that the susceptibility and vulnerability to floods and landslides are minimised.

Recommendations

In order to enable future research in the assessed field, several recommendations for governmental institutions and organisations are suggested, as a result of experiences and of conclusions drawn from the work of this thesis. Firstly, the difficulties in accessing data from ministries and organisations was a clear sign of a challenge that Rwanda faces. This has also been identified by the RWB and RLMUA, which mentions several important measures for a more sustainable water resource management, and to reduce the risks with and consequences of floods and landslides. If the ambitious government measures are implemented, there might still be a lot of work needed for the long-term realisation of these and to have people on all levels of the society working together. The measures presented by the RWB and RLMUA that are considered most important to prioritise in order to limit the vulnerability of Bakokwe catchment, as a result of this thesis, are:

- Increasing the extent of terraces plantations in hilly areas.
- Further conserving natural forests and developing agroforestry.
- Improving monitoring of rainfall, river flow, and groundwater.
- Develop collaborations between institutions on flood forecasting and early warning systems

- Enhancing data recording and information management systems and developing related databases.

- Contributions to the local inhabitants in self-preparedness and awareness.

The ones considered most suitable for the catchment is implementing terrace plantations throughout the catchment and pedagogical contributions to the local inhabitants of the area, which also is stated as important by two of the respondents to the questionnaire. These two measures have to be implemented in accordance in order for them to have the greatest effect. If not, the risk of conflict and distrust can spread in the communities and in order for a community to adapt, it is necessary for the people to fully understand the reason behind the adaptation.

Furthermore, reliable measurements of the catchment's hydrological situation are of great importance if more research is to be conducted. In this thesis, the availability of good and covering data has been one of the main limitations and thus it is highly recommended that information is made more easily accessible and more data is gathered. The reports on consequences of disasters by MINEMA are recommended to be validated and more thoroughly described in terms of how, and when, data was collected and defined, for them to be more valuable. It is also necessary that more information about the quality of the rainfall data from METEO is presented and described thoroughly in order to facilitate the usage of the rainfall data. During the work with this thesis, data from METEO was retrieved on several occasions. The recorded rainfall for the same station, during the same day, showed at times different levels of rainfall from the different retrieved sets of data. This is recommended to be improved by scanning and evaluating the data. The measurements of total suspended solids performed in this work were deemed reliable and easy to perform, thus additional measurements are recommended to be regularly conducted by a governmental institution on well distributed locations in every catchment. Such measurements give clear indications of the erosion status and would make it easier to decide which areas to focus the actions to minimise erosion on.

Conclusion

The history of occurrence and impacts of heavy rainfalls, floods, and landslides in Rwanda have only been sparsely documented and only a few reports have been found from the last 40 years. However, the analysis of the precipitation data implies that the occurrence has been underreported. A high increase in population, intense urbanisation, heavy rainfall, and drastic changes in land use and land cover are likely to have increased the occurrence and susceptibility to floods and landslides in the area. For future outlooks, the predicted population growth rate and the consequent changes in livelihoods and land cover, will increase the number of people, animals and infrastructure exposed to consequences of heavy rainfall. This, together with an expected intensified hydrological cycle as a result of climate change, will further increase the susceptibility of Bakokwe catchment to floods and landslides.

Further research in this field is needed, as the limited amount of available data has restricted the analysis and led to uncertainty in the conclusions. To facilitate this, it is suggested that governmental institutions collaborate more closely and that data are made more accessible. Furthermore, it will be of importance that the proposed measures by governmental ministries are implemented, such as increasing the extent of terrace plantations and evaluating existing data, and enhancing data collection on rainfall, river flow and natural disasters. The implementations of these measures are suggested to be reported and evaluated regularly. Such evaluations should be publicly available to enable future research.

References

Asumadu-Sarkodie, S; Rufangura, P; Jayaweera, H. MPC.; Asantewaa Owusu, P. 2015. Situational Analysis of Flood and Drought in Rwanda. *International Journal of Scientific & Engineering Research* 6(8). doi:10.6084/M9.FIGSHARE.3381463.V1

BBC NEWS. 2016. Rwanda: Landslides caused by heavy rains kill dozens. *BBC NEWS.* 9 May. https://www.bbc.com/news/world-africa-36248334. (Accessed 2022-02-20).

BBC NEWS. 2018. Rwanda landslides after heavy rain bring 2018 death toll to 200. *BBC NEWS*. 7 May. https://www.bbc.com/news/world-africa-44031799. (Accessed 2022-02-20).

European Committee for Standardization [CEN]. 2021. EN ISO 748:2021. *Hydrometry – Measurement of liquid flow in open channels – Velocity area methods using point velocity measurements.* 3d ed. Brussels: CEN.

ESRI. 2022. *Sentinel-2 10m land cover time series of the world from 2017-2021*. https://www.arcgis.com/home/item.html?id=d3da5dd386d140cf93fc9ecbf8da5e31. (Accessed 2022-03-24).

Famine Early Warning Systems Network [FEWS NET]. 2015. *Rwanda: Floods Emergency Plan of Action (EPoA) DREF Operation n° MDRRW011. https://reliefweb.int/report/rwanda/rwanda-floods-emergency-plan-action-epoa-dref-operation-n-mdrrw011* (Accessed 2022-03-20).

Famine Early Warning Systems Network [FEWS NET]. 2016. *Stable food security outcomes continue despite landslides in northern areas.* https://fews.net/east-africa/rwanda/key-message-update/may-2016 (Accessed 2022-03-20).

Famine Early Warning Systems Network [FEWS NET]. 2018. *Flooding and landslides inflict heavy toll on livelihoods and cropping conditions.* https://fews.net/east-africa/rwanda/key-message-update/may-2018. (Accessed 2022-03-20).

Famine Early Warning Systems Network [FEWS NET]. 2020. *Global Weather Hazards Summary*. https://fews.net/sites/default/files/documents/reports/GlobalWeatherHazard-03.01.20.pdf (Accessed 2022-03-20).

Gahakwa, D.; Asiimwe, T; Nabahungu, N.L.; Mutimura, M.; Isibo, T.; Mutaganda, A.;Ngaboyisonga, C. 2014. A Decade of Agricultural Research in Rwanda: Achievements and the Way Forward. In Bernard Vanlauwe, Piet van Asten, Guy Blomme. *Challenges and Opportunities for Agricultural Intensification of the Humid Highland Systems of Sub-Saharan Africa.* Switzerland: Springer Cham, 69-80.

Global Forest Watch. 2022. *Rwanda.* https://www.globalforestwatch.org. (Accessed 2022-04-03).

Hakizimana, Eustache; Wali, U. G.; Sandoval1, D.; Venant, Kayibanda. 2020. Environmental Impact Assessment of Hydropower Plants in Rwanda: Nyabarongo I Hydropower Plant (NHPP I). *Energy and Environmental Engineering 7(2): 27-37.* doi: 10.13189/eee.2020.070202

Hamill, Les. 2011. *Understanding Hydraulics.* Red Globe Press. ISBN: 9780230242753

Hishamunda, Alphonse; Ag. Director of Prevention and Mitigation Unit at the Ministry in charge of Emergency Management [MINEMA]. 2022. Intervju and email contact. April 29th.

Houghton, Sir John. 2015. *Global Warming*. Cambridge University Press. ISBN: 9781107463790

IPCCa. 2022. Chapter 4: Water. IPCC WGII Sixth Assessment Report. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* https://www.ipcc.ch/assessment-report/ar6/ (Accessed 2022-04-15).

IPCCb. 2022. Chapter 9: Africa. IPCC WGII Sixth Assessment Report. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* https://www.ipcc.ch/assessment-report/ar6/ (Accessed 2022-04-15).

Jones, A.;Breuning-Madsen, H.; Brossard, M.; Dampha, A.; Deckers J.; Dewitte, O.; Gallali, T.; Hallett, S.; Jones, R.; Kilasara, M.; Le Roux, P.; Micheli, E.; Montanarella, L.; Spaargaren, O.; Thiombiano, L.; Van Ranst, E.; Yemefack, M.; Zougmoré R. (eds.). 2013. Soil Atlas of Africa. *European Commission, Publications Office of the European Union, Luxembourg.* 176 pp. https://esdac.jrc.ec.europa.eu/content/soil-map-soil-atlas-africa#tabs-0-description=0. (Accessed 2022-02-22)

Kamonyi District. 2018. *Kamonyi District Development Strategy (2018-2024).* https://knowledge-uclga.org/IMG/pdf/kamonyidistrict.pdf (Accessed 2022-04-03).

Kamonyi District. 2022. *Ahabanza*. https://www.kamonyi.gov.rw/ (Accessed 2022-04-05).

Karamage, F; Zhang, C; Kayiranga, A; Shao, H; Fang, X; Ndayisaba, F; Nahayo, L; Mupenzi, C; Tian, G. 2016. USLE-Based Assessment of Soil Erosion by Water in the Nyabarongo River Catchment, Rwanda. *International Journal of Environmental Research and Public Health*. 13(835). doi:10.3390/ijerph13080835

Kulimushi, L.C; Choudhari, P; Maniragabaa, A; Elbeltagi, A; Mugabowindekwe, M; Rwanyiziri, G; Byizigirof R.V; Murlidhar Pingale, S; Singh S.K. 2021. Erosion risk assessment through prioritization of sub-watersheds in Nyabarongo river catchment, Rwanda. *Environmental Challenges.* 5. ISSN 2667-0100, https://doi.org/10.1016/j.envc.2021.100260.

Kwisanga, J-M. P. 2017. *Assessing Flood Risk And Developing A Framework For A Mitigation Strategy Under Current And Future Climate Scenarios In Nyabarongo Upper Catchment, Rwanda.* Institute of Water and Energy Sciences (Including Climate Change), Pan African University. http://repository.pauwes-cop.net/handle/1/141

Li

Meng, X. 2022. Landslide. *Encyclopedia Britannica*, https://www.britannica.com/science/landslide. (Accessed 2022-04-17).

METEO. 2019. *METEO Rwanda Services Portal*. http://mis.meteorwanda.gov.rw/user/login?destination=/data-requests. (Accessed 2022-03-10).

METEO. 2022. *METEO Rwanda Services Portal*. http://mis.meteorwanda.gov.rw/user/login?destination=/data-requests. (Accessed 2022-04-08).

Ministry of Disaster Management and Refugee Affairs [MIDIMAR]. 2015. *The National Risk Atlas of Rwanda*. https://www.gfdrr.org/sites/default/files/publication/National_Risk_Atlas_of_Rwanda_electronic_version_0.pdf (Accessed 2022-04-10).

Ministry of Environment. 2019. Rwanda Forest Cover Mapping. https://www.environment.gov.rw/fileadmin/user_upload/Moe/Publications/Reports/Forest_cover_report_2019.pdf (Accessed 2022-03-37)

Ministry of Finance and Economic Planning [MINECOFIN]. 2012. *Vision 2020.* https://kigalicity.gov.rw/fileadmin/templates/Documents/policies/Rwanda_Vision_2020__revised_2012_.pdf. (Accessed 2022-02-10).

Ministry of Finance and Economic Planning [MINECOFIN] . 2020. *Vision 2050*. https://www.nirda.gov.rw/uploads/tx_dce/Vision_English_Version_2050_-31_Dec_2020.pdf. (Accessed 2022-02-10).

Ministry in charge of Emergency Management [MINEMA]. 2017. *Annual Disaster Effects Report 2016.* https://www.minema.gov.rw/index.php?eID=dumpFile&t=f&f=9437&token=8193dd26daa46e2b4f35ede04e28712b65b87db0. (Assessed 2022-02-20).

Ministry in charge of Emergency Management:a [MINEMAa]. 2018. *Annual Disaster Effects Report 2017.* https://www.minema.gov.rw/index.php?eID=dumpFile&t=f&f=9438&token=d035d745ba0f7cb474e249ce3ec2301f5d4cb3d4 (Accessed 2022-02-20).

Ministry in charge of Emergency Management:b [MINEMAb]. 2018. *National Contingency Plan For Floods and Landslides*. https://www.minema.gov.rw/fileadmin/user_upload/Minema/Publi cations/Contingency_Plans/Contingency_Plan_for_Floods_nd_Landslides.pdf (Accessed 2022-03-02).

Ministry in charge of Emergency Management [MINEMA]. 2019. *Annual Disaster Effects Report 2018.* https://www.minema.gov.rw/index.php?eID=dumpFile&t=f&f=9436&token=5d62a86fdef5def2761f7eeea16bc4c5d32656de (Accessed 2022-02-20).

Ministry in charge of Emergency Management [MINEMA]. 2020. *Annual Disaster Effects Report 2019. https://www.minema.gov.rw/index.php?eID=dumpFile&t=f&f=9424&token=e9857cd8e28bc9a63b9ff2caeb14ce90344bbb84* (Accessed 2022-02-20).

Ministry in charge of Emergency Management [MINEMA]. 2021. *Disaster Damages January - December 2020.* https://www.minema.gov.rw/index.php?eID=dumpFile&t=f&f=15706&token=beae50639649752a098c33b3793101c3f1da961a (Accessed 2022-02-20).

Mind'je, R; Li, L; Amanambu, A.C; Nahayo, L; Nsengiyumva, J.B; Gasirabo, A and Mindje, M. 2019. Flood Susceptibility Modeling and Hazard Perception in Rwanda. *International Journal of Disaster Risk Reduction.* Vol. 38 2019, article 101211. https://doi.org/10.1016/j.ijdrr.2019.101211

Mikova, K; Makupa, E and Kayumba, J. 2015. Effect of Climate Change on Crop Production in Rwanda. *Earth Sciences*. Vol. 4, No. 3, pp. 120-128. doi: 10.11648/j.earth.20150403.15

Muhanga District. 2018. *Muhanga District Development Strategy 2018-2024.* https://www.muhanga.gov.rw/fileadmin/user_upload/muhanga/Inyandiko/Igenamigambi/Muhanga_DDS_2018_2024_Final_Version.pdf (Accessed 2 April 2022).

Muhanga District. 2022. *Ahabanza.* https://www.muhanga.gov.rw/ Accessed 5 April 2022.

Nahayo, L; Nsengiyumva, J-B; Mupenzi, C; Mind'je, R and Nyesheja, E. M. 2019. Climate Change Vulnerability in Rwanda, East Africa. *International Journal of*

Geography and Geology. Vol. 8, No. 1, pp. 1-9. doi: 10.18488/journal.10.2019.81.1.9

National Geographic Society. 2018. Erosion. *Resource Library*. https://www.nationalgeographic.org/encyclopedia/erosion/#:~:text=Encyclopedic%20Entry%20Vocabulary-,Erosion%20is%20the%20geological%20process%20in%20which%20earthen%20materials%20are,but%20does%20not%20involve%20movement. (Accessed 2022-04-17).

Ndekezi, F-X. 2010. *Hydrological modelling of Nyabarongo River basin in Rwanda using combinations of precipitation input from meteorological models, remote sensing, and ground station measurements.* UNESCO-IHE Institute for Water Education, Delft, the Netherlands. ISBN-13: 978-3-659-24534-3.

Nkurunziza Michel a. 2022. Disasters kill 15, injure 37 in less then a month. *The New Times.* January 27. https://www.newtimes.co.rw/news/disasters-kill-15-injure-37-less-month. (Accessed 2022-03-17).

Nkurunziza Michel b. 2022. Floods, landslides paralyse transport in some districts. *The New Times*. 10 February. https://www.newtimes.co.rw/news/floods-landslides-paralyse-transport-some-districts. (Accessed 2022-03-17)

Nkurunziza Michel c. 2022. Government sheds light on two-month disaster status, blames climate change. *The New Times.* 20 February. https://www.newtimes.co.rw/news/government-sheds-light-two-month-disaster-status-blames-climate-change (Accessed 2022-03-17).

Novella, Nicholas S. and Thiaw, Wassila M. 2013. African Rainfall Climatology Version 2 for Famine Early Warning Systems. *Journal of Applied Meteorology and Climatology*. 52(3): 588-606. Doi: https://doi.org/10.1175/JAMC-D-11-0238.1

Nsengiyumva. 2012. *Disaster High Risk Zones on Floods and Landslides.* https://www.preventionweb.net/files/28208_highriskzonesreportfinalpublication.pdf (Accessed 2022-03-15).

Nsengiyumva, J-B; Valentino, R. 2020. (2020) Predicting landslide susceptibility and risks using GIS-based machine learning simulations, case of upper Nyabarongo catchment. *Geomatics, Natural Hazards and Risk*. 11(1): 1250-1277. DOI:10.1080/19475705.2020.1785555.

OCHA: Regional Office for Southern and Eastern Africa [ROSEA]. 2021. *Rwanda - Subnational Administrative Boundaries*. National Institute of Statistics of Rwanda [NISR]. https://data.humdata.org/dataset/cod-ab-rwa. Accessed 10 March 2022.

OCHA: United Nations Office for the Coordination of Humanitarian Affairs. 2021. *Disasters: Rwanda, Floods ongoing and past.* https://reliefweb.int/disasters?search=rwanda%20floods

Open Data Site RCMRD. 2022. *Rwanda Land Cover Scheme.* https://opendata.rcmrd.org/search?q=rwanda%20land%20cover. Accessed 10 March 2022.

Reliefweb. 2010. *Rwanda: Rubavu Landslide DREF operation n° MDRRW006 Final Report.*https://reliefweb.int/report/rwanda/rwanda-rubavu-landslide-dref-operation-n%C2%B0-mdrrw006-final-report. (Accessed 2022-03-04).

Reliefweb. 2011. *Rwanda: Heavy Rainstorms & Floods DREF operation n° MDRRW00.*https://reliefweb.int/report/rwanda/rwanda-heavy-rainstorms-floods-dref-operation-n%C2%B0-mdrrw007 (Accessed 2022-03-04).

Reliefweb. 2012.*Thousands affected by heavy rains and floods in Rwanda.* https://reliefweb.int/report/rwanda/thousands-affected-heavy-rains-and-floods-rwanda (Accessed 2022-03-04).

Reliefweb. 2017. *Rwanda: Storm and Heavy Winds DREF Emergency Plan of Action (EPoA) MDR015.* https://reliefweb.int/report/rwanda/rwanda-storm-and-heavy-winds-dref-emergency-plan-action-epoa-mdr015. (Accessed 2022-03-04).

Reliefweb. 2018. *Rwanda – Flood (Rwanda Meteorology Agency, Media) (ECHO Daily Flash of 27 April 2018). https://reliefweb.int/report/rwanda/rwanda-flood-rwanda-meteorology-agency-media-echo-daily-flash-27-april-2018* . (Accessed 2022-03-04).

Reliefweb. 2019. *Rwanda: Floods - Emergency Plan of Action - DREF n° MDRRW018.* Reliefweb. https://reliefweb.int/report/rwanda/rwanda-floods-emergency-plan-action-dref-n-mdrrw018. (Accessed 2022-03-04)

Reliefweb:a. 2020. *Rwanda - Floods and mudslides update (Rwanda Meteorology Agency, NOAA, media) (ECHO Daily Flash of 5 February 2020).* https://reliefweb.int/report/rwanda/rwanda-floods-and-mudslides-update-rwanda-meteorology-agency-noaa-media-echo-daily. (Accessed 2022-03-04)

Reliefweb:b. 2020. *Rwanda: Floods and Windstorm - Emergency Plan of Action - DREF n° MDRRW019*. https://reliefweb.int/report/rwanda/rwanda-floods-and-windstorm-emergency-plan-action-dref-n-mdrrw019. (Accessed 2020-04-02)

Reliefweb. 2021. *Rwanda: Floods and Windstorm - Emergency Plan of Action (EPoA), DREF Operation n° MDRRW020.* Reliefweb. https://reliefweb.int/report/rwanda/rwanda-floods-and-windstorm-emergency-plan-action-epoa-dref-operation-n-mdrrw020. (Accessed 2022-03-04).

Rwanda Land Management and Use Authority [RLMUA]. 2020. *National Land Use & Development Master Plan 2020-2050.* https://rlma.rw/fileadmin/user_upload/National_Land_Use_DevMaster_Plan_2020-2050.pdf (Assessed 25 February 2022)

Rwanda Land Management and Use Authority:a [RLMUAa]. 2021. *Kamonyi District Profile.*https://geodata.rw/portal/apps/sites/#/nsdi/pages/kamonyi (Assessed 2022-02-22).

Rwanda Land Management and Use Authority:b [RLMUAb]. 2021. *Muhanga District Profile.* https://geodata.rw/portal/apps/sites/#/nsdi/pages/muhanga (Assessed 22 February 2022).

Rwanda Water Resource Board [RWB] 2021. *Rwanda Water Resource Boards Strategic Plan.* https://www.rwb.rw/fileadmin/user_upload/RWRB/Documents/Rwanda_Water_Resources_Board_Strategic_Plan.pdf (Assessed 2022-02-23)

Rwanda Water Resource Board:a [RWBa]. 2022. *Lower Nyabarongo (NNYL).* https://waterportal.rwb.rw/catchment-level-1/30 (Accessed 10 February 2022)

Rwanda Water Resource Board:b [RWBb]. 2022. *Surface water*. https://waterportal.rwb.rw/data/surface_water. (Accessed 2022-02-25.)

Siebert, A; Dinku, T; Vuguziga, F; Twahirwa, A; Kagabo, D. M.; delCorral, J; Robertson, A. W.; et al. 2019. Evaluation of ENACTS-Rwanda: A new multi-decade, high-resolution rainfall and temperature data set—Climatology. *Int J Climatol.* 39: 3104– 3120. https://doi.org/10.1002/joc.6010

The New Humanitarian. 2012. Floods displace hundreds in Rwanda. *The New Humanitarian.* 18 April. https://www.thenewhumanitarian.org/news/2012/04/18/floods-displace-hundreds-rwanda (Accessed 2022-04-05)

The World Bank Group. 2022. *Population density (people per sq. km of land area) - Rwanda.* https://data.worldbank.org/indicator/EN.POP.DNST?locations=RW (Accessed 2022-04-05).

The World Bank. 2020. *Rwanda.* https://data.worldbank.org/country/rwanda. (Accessed 2022-04-05).

Union of International Associations [UIA]. 2019. Flash floods. *The Encyclopedia Of World Problems & Human Potential*. http://encyclopedia.uia.org/en/problem/132948. (Accessed 2022-04-17).

Union of International Associations [UIA]. 2022. Riverine floods. *The Encyclopedia Of World Problems & Human Potential*. http://encyclopedia.uia.org/en/problem/riverine-floods. (Accessed 2022-04-17).

Appendix

A.1 Work process in QGIS

In this part of the appendix the full work process performed in QGIS is presented together with all metadata and sources. OpenData was used throughout the process to retrieve the most updated information on river courses, water bodies, roads, cities and settlements. The use of this information is considered to not need explanation in the form of a flowchart, and will thus be neglected in this section.

A.1.1 Delineation of Bakokwe subcatchment

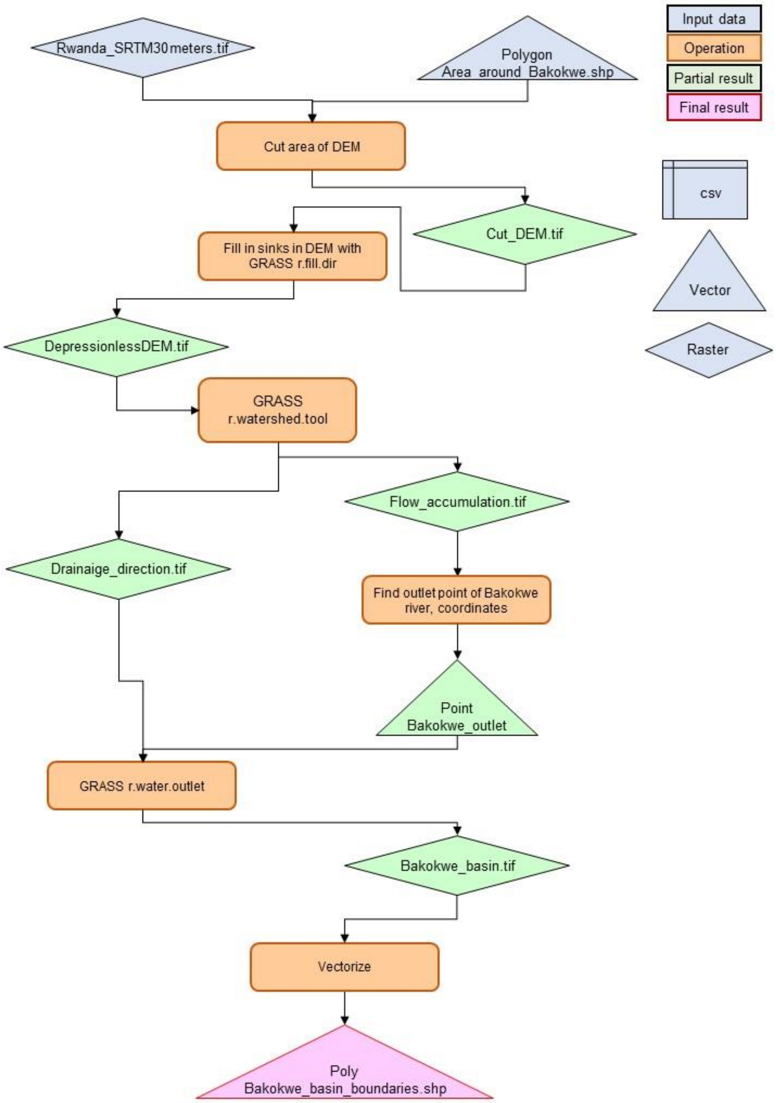


Figure A1. Flowchart of work process to identify land cover of the catchment.

A.1.2 Creation of the LULC map of 2020

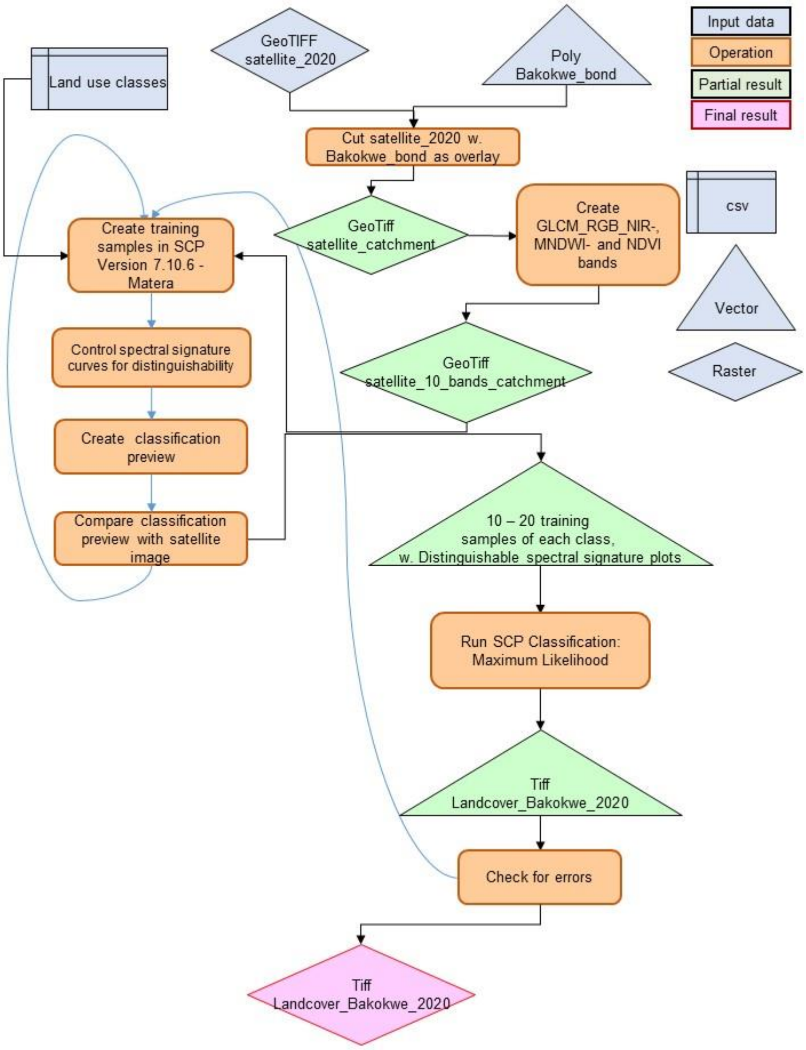


Figure A2. Flowchart of work process to identify land cover of the catchment.

A.1.3 Interpolation of rain data

The rain data retrieved from the meteorological stations of METEO, and from the ARC2 Database, was normalised and then interpolated over the Nyabarongo catchment and Bakokwe subcatchment. The procedure is presented in figure A3.

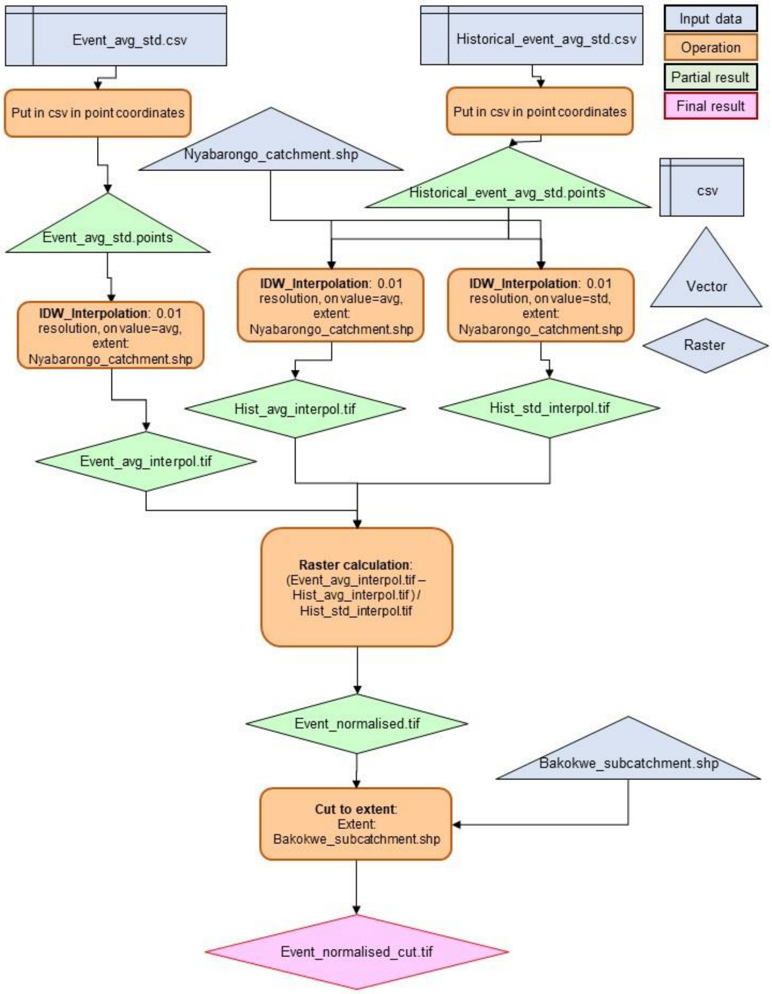


Figure A3. Flowchart of work process to normalise and interpolate daily rainfall data over the catchment.

A.1.4 Metadata

Table A1. The metadata used when using QGIS to get delineation of Bakokwe subcatchment, land cover maps and analysis and precipitation estimates.

File name	File type	Source	Coord. system	Information
Rwanda Land Cover 1990 Scheme I	.tif	RCMRD-SERVIRESA,The Goverment of Rwanda, NASA, USAID, USEPA, 2018	EPSG:4326 - WGS 84	ODbL 1.0 license
Rwanda Land Cover 2000 Scheme I	.tif	RCMRD-SERVIRESA,The Goverment of Rwanda, NASA, USAID, USEPA, 2018	EPSG:4326 - WGS 85	ODbL 1.0 license

Rwanda Land Cover 2010 Scheme I	.tif	RCMRD-SERVIRESA,The Goverment of Rwanda, NASA, USAID, USEPA, 2018	EPSG:4326 - WGS86	ODbL 1.0 license
Rwanda Land Cover 2015 Scheme I	.tif	Rwanda, RCMRD 2018	EPSG:4326 - WGS87	ODbL 1.0 license
Landcover_2017_18_19_20_21	.tif	Esri Inc, 2022. Karra, Kontgis, et al. “Global land use/land cover with Sentinel-2 and deep learning.” IGARSS 2021-2021 IEEE International Geoscience and Remote Sensing Symposium.	WGS84-UTM	Source imagery: Sentinel-2. Variable mapped: Land use/land cover in 2017, 2018, 2019, 2020, 2021. Information: https://www.arcgis.com/home/item.html?id=d3da5dd386d140cf93fc9ecbf8da5e31

Administrative_borders	.shp, .xlsx	National Institute of Statistics of Rwanda (NISR), 2018-2022.	EPSG:4326-WGS87	Contributer; OCHA Regional Office for Southern and Eastern Africe (ROSEA)
Subnational Population Statistics	.csv	United States Census Bureau, 2021	-	Population in district and sectors of Rwanda.
Catchment Level 1	.shp	Rwanda Water Resources Board, 2020, through SHER Ingénieurs-Conseils and Rwanda Natural Resources Authority.	EPSG:32735	Public Domain

Catchment Level 2	.shp	Rwanda Water Resources Board, 2020, through SHER Ingénieurs-Conseils and Rwanda Natural Resources Authority.	EPSG:32735	Public Domain
Catchment Level 3	.shp	Rwanda Water Resources Board, 2020, through SHER Ingénieurs-Conseils and Rwanda Natural Resources Authority.	EPSG:32735	Public Domain
Rwanda SRTM DEM 30 meters	.tif	NASA, USGS, SERVIR-RCMRD 2018.	EPSG:4326 - WGS 84	"Data represents the Shuttle Radar Topography Mission (SRTM) 30 metres image for Rwanda. These SRTM were created through mosaicking tiles and clippingto the extent of the country." Open Data Base Liscence

Rwanda_latest_free	Archive: .shp	Geofabrik, 2022-02-27	EPSG:4326 - WGS84	The files in this archive have been created from OpenStreetMap data and are licensed under the Open Database 1.0 License. See www.openstreetmap.org for details about the project.
Sat_image	.tif	Landsat-8, Downloaded with GoogleEarth Enginge, 2020	EPSG:4326 - WGS84	Satellite imagery from Landsat 8, images throughout the year are combined.
Rain_sat	.csv	ARC2: https://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.FEWS/.Africa/.DAILY/.ARC2/.daily/index.html?Set-Language=en		Text file of daily precipitation from 1st of January 1983, up until 1st of May 2022, covering the extent of Nyabarongo catchment.

A.1.5 Locations

The coordinates of all visited locations during field visits are presented in Table A2 and the coordinates of all hydrological stations are presented in Table A3.

Table A2. Name, ID and coordinates of observation points.

ID	Name	Longitud	Latitud
1	Gatare river, METEO station	29.76046	-1.93473
2	Bakokwe river, upstream	29.77305	-1.92979
3	Gasayo river	29.76993	-1.91464
4	Mutumba, clear river	29.77196	-1.90819
5	Kayumbu, bridge	29.79758	-1.89542
6	Confluence, Bakokwe/ Kayumbu	29.79744	-1.89395
7	Bakokwe, after confluence Kayumbu	29.79738	-1.89371

8	Bakokwe river, bridge	29.81232	-1.85646
9	Nyabarongo, before confluence Bakokwe	29.81402	-1.8526
10	Nyabarongo, after confluence Bakokwe	29.81891	-1.85457
11	Nyabarongo, after confluence Nyabogogo	30.00391	-1.96072

Table A3. Name, ID and coordinates of hydrological stations in the Nyabarongo catchment.

ID	Station Name	Latitud	Longitud	In Nyabarongo
1	Gitega	-1.96	30.06	Lower
2	Butamwa	-2.01	30.03	Lower
3	Kigali Aero	-1.95	30.11	Lower
4	Rulindo	-1.71	29.91	Lower
5	Rutongo	-1.81	30.05	Lower

6	Rushashi	-1.73	29.86	Lower
7	Byumba Met	-1.6	30.05	Lower
8	Rwamagana	-1.93	30.43	Lower
9	Musha	-1.91	30.35	Lower
10	Kayonza	-1.9	30.5	Lower
11	Kawangire	-1.81	30.43	Lower
12	Ruramba	-2.55	29.51	Upper
13	Gikongoro Met	-2.48	29.55	Upper
14	Kaduha	-2.33	29.53	Upper
15	Mushubi	-2.36	29.45	Upper
16	Byimana	-2.16	29.71	Upper

17	Kibangu	-1.83	29.68	Upper
18	Nyange-Ngor	-2.05	29.58	Upper
19	Sovu	-1.91	29.52	Upper
20	Rwaza	-2.53	29.68	Upper
21	Kivumu	-2.05	29.8	Lower
22	Gacurabwenge	-2.1	29.91	Lower
23	Nyabinoni	-1.76	29.68	Upper
24	Nyamabuye	-2.08	29.78	Upper
25	Rugendabari	-1.95	29.66	Upper

A.2 Results

The results from the measurements conducted during the field visit, retrieved data, and the questionnaire together with the collected answers, are presented in this section.

A.2.1 Data gathered from MINEMA reports and personal contact

Data from the Annual Disaster Reports was gathered from the MINEMA on reported events in Muhanga and Kamonyi between 2016 and 2020. Through meetings via telephone and email conversations with Mr. Alphonse Hishamunda, data from the not yet published Annual Disaster Report for 2021 from MINEMA, was retrieved. The utilised data is presented in table A4.

Table A4. Total number of reported cases for 2016-2021 due to natural disasters in Muhanga and Kamonyi district. (data from MINEMA, 2021; Hishamunda, 2022).

	Muhanga						Kamonyi					
	2016	2017	2018	2019	2020	2021	2016	2017	2018	2019	2020	2021
Loss of human lives	18	8	3	2	23	4	0	3	15	2	5	4
Human injuries	7	4	1	1	9	27	1	2	9	1	13	3
Loss of crop [Ha]	293	35	3	23	7	57.7	365	71	356	72	14	2

Damage to property	281	46	254	28	253	91	78	216	2554	52	136	5
Loss of livestock	21	0	6	3	3	6	1	124	0	2	8	2
Damage to roads	1	2	2	0	18	2	0	0	11	2	8	0
Damage to bridges	0	1	4	0	9	5	0	1	11	2	14	1
Damage to churches	0	3	0	0	1	1	0	0	0	0	1	0
Damage to adm. offices	0	0	0	0	1	1	0	1	0	0	0	0
Damage to water supply	0	0	0	0	0	0	0	0	0	0	2	0

Damage to classrooms	0	2	0	0	14	17	0	0	1	5	0	11
Damage to transm. lines	0	0	1	0	2	2	0	1	1	1	26	0

A.2.2 TSS-data

On the first of March 2022, TSS was measured at eight locations in the Bakokwe subcatchment, and at one location further downstream of the Nyabarongo river. The result of these measurements are presented in Table A5, the name of the locations can be found in table A3 in section A.1.5

Table A5. Measured TSS-concentrations in milligrams per litre at the measuring points, ranked after observation-IDs.

ID	1	3	4	5	7	8	9	10	11
TSS [mg/l]	402	964	19	271	545	656	3235	1735	4950

A.3 Questionnaire

A.3.1 The distributed questionnaire

"Flood events in Nyabarongo catchment"

NAME: ____
POSITION: ____
CONTACT INFORMATION:_________________________________

INSTITUTION:____

1. What do you consider being the main consequence of flooding in the Nyabarongo catchment and Bakokwe subcatchment?

2. Have you identified one area as the area mostly exposed to floods in the Nyabarongo catchment and Bakokwe subcatchment?

3. Are there any records of floods and their consequences in the area and how can these be accessed?

4. Are there records of land use and land cover and how can these be accessed?

5. What are your thoughts on sediment transport and the ecological status of rivers in the area?

6. What solutions would you like to implement in order to prevent damage caused by floods?

In questions 7 - 10 you are asked to rank the likeliness of a consequence of floods. Please do so according to the time you have available and your personal perception of the surroundings of the catchment. You are most welcome to add comments.

7. How likely is it that floods cause a reduction in agricultural productivity and loss of livestock?

1	2	3	4	5	6
Not likely	Possible	Likely	Very likely	Most likely	Certain

Optional comment:

____

8. How likely is it that floods cause roads to become impassable / non usable?

1	2	3	4	5	6
Not likely	Possible	Likely	Very likely	Most likely	Certain

Optional comment:

____

9. How likely is it that floods cause loss of human life?

1	2	3	4	5	6

Not likely	Possible	Likely	Very likely	Most likely	Certain

Optional comment:
____

10. How likely is it that floods cause damage to house property?

1	2	3	4	5	6
Not likely	Possible	Likely	Very likely	Most likely	Certain

Optional comment:
____

Other comments or additional information:

Thank you for your participation and contribution!

A.3.2 Collected answers to questionnaire

Answers to the questionnaire were collected from RWB, MINEMA and Muhanga, and Kamonyi, district offices. No questionnaires had been filled by RLMUA by the time of collection - four weeks after the distribution. Questions 1-6 were all written answers and they were summarised according to the best possible ability to convey and present a truthful summary. Questions 7-10 were all answered with a number ranging from 1 to 6, to rank the likeness of an event. The numbers correspond to the following perception: 1 = Not likely, 2 = Possible, 3 = Likely, 4 = Very Likely, 5 = Most Likely, 6 = Certain.

The questionnaire was filled by the following persons:

- Name: Alsaad Ndayizeye
  Institution: RWB
  Position: River Flood Control Specialist

- Name: Niragire Ezechiel
  Institution: Muhanga district - Local Administrative Entities Development Agency [LODA]
  Position: Environmental & Social Safeguards Specialist

- Name: Nzabahimana James
  Institution: Kamonyi district
  Position: Water and sanitation officer

- Name: Alphonse Hishamunda
  Institution: MINEMA
  Position: Ag. Director of Prevention and Mitigation Unit

The answers are compiled so that all respondents' answer to one question is presented at the same place. It is clearly stated who answered what.

1. What do you consider being the main consequence of flooding in the Nyabarongo catchment and Bakokwe subcatchment?

Name: Alsaad Ndayizeye

Institution: Rwanda WRB

Position: River Flood Control Specialist

Answer: The main consequences are loss of lives, loss of properties, infrastructure damages, loss of agricultural production, etc.

Name: NIRAGIRE Ezechiel

Institution: LODA Staff based in Muhanga District

Position: Environmental & Social Safeguards Specialist

Answer: - Siltation of Nyabarongo and bakokwe river by soil carried out by erosion

- Loss of people/farmers properties mainly crops
- Pollution of water bodies
- Destruction of people and public (Roads, water supply etc) infrastructures

Name: NZABAHIMANA James

Institution: Kamonyi district

Position: Water and sanitation officer

Answer: The main consequence of flooding includes loss of human life, damage to infrastructures properties, destruction of crops, loss of livestock, and deterioration of health conditions owing to waterborne diseases.

Name: Alphonse Hishamunda

Institution: MINEMA

Position: Ag. Director of Prevention and Mitigation Unit

Answer: High runoff due to steep slopes, insufficient anti-erosive measures (trenches, terraces, soil fixing plants and grasses) and lack of rainwater harvesting systems

2. Have you identified one area as the area mostly exposed to floods in the Nyabarongo catchment and Bakokwe subcatchment?

Name: Alsaad Ndayizeye

Institution: Rwanda WRB

Position: River Flood Control Specialist

Answer: *No, there are different areas, but not yet ranked.*

Name: NIRAGIRE Ezechiel

Institution: LODA Staff based in Muhanga District

Position: Environmental & Social Safeguards Specialist

Answer: The mostly expose is agriculture activities along Nyabarongo and Bakokwe river as most of time during rainy season crops are damaged by flood and landslide. But also infrastructure (roads and bridges) are damaged by flood.

Name: NZABAHIMANA James

Institution: Kamonyi district

Position: Water and sanitation officer

Answer: yes, we identified the area mostly exposed to floods in the Nyabarongo catchment namely kumwaro and busharara (Murambi village muyange cell kayumbu sector)and kayenzi sector (cubi cell and kirwa cell) ngamba sector (Kabuga cell) and in Runda Sector.

Name: Alphonse Hishamunda

Institution: MINEMA

Position: Ag. Director of Prevention and Mitigation Unit

Answer: Vunga-Shyira-Ndiza Corridor in Nyabarongo Catchment

3. Are there any records of floods and their consequences in the area and how can these be accessed?

Name: Alsaad Ndayizeye

Institution: Rwanda WRB

Position: River Flood Control Specialist

Answer: No, I don’t have. You can consult MINEMA on this information.

Name: NIRAGIRE Ezechiel

Institution: LODA Staff based in Muhanga District

Position: Environmental & Social Safeguards Specialist

Answer: Floods records are at Sector level, whereby sector agronomist record damages of crops due to flood. To access them is to ask sector agronomist or District agronomist.

Name: NZABAHIMANA James

Institution: Kamonyi district

Position: Water and sanitation officer

Answer: We didn’t make the records of floods and their consequences.

Name: Alphonse Hishamunda

Institution: MINEMA

Position: Ag. Director of Prevention and Mitigation Unit

Answer: Roads and bridge infrastructures have been severely affected and destroyed/damaged over the last years. A joint assessment was conducted by different institutions in the area and a report was submitted to the Prime Minister's Office for consideration. It cannot be shared.

4. Are there records of land use and land cover and how can these be accessed?

Name: Alsaad Ndayizeye
Institution: Rwanda WRB

Position: River Flood Control Specialist

Answer: Yes, it's available. Refer to the shared files.

Name: NIRAGIRE Ezechiel

Institution: LODA Staff based in Muhanga District

Position: Environmental & Social Safeguards Specialist

Answer: The record of land use and land cover can be accessed through the District land use master plan. On the recently RLMUA launched National Spatial Data Infrastructure Hub, RLMUA has created a page specific for Muhanga District. This page provides access to the draft land use plan (including the Muhanga Satellite City part), appropriate for public display. This is the link *https://geodata.rw/portal/apps/sites/#/nsdi/pages/muhanga* to explore the executive summary and the application

Name: NZABAHIMANA James

Institution: Kamonyi district

Position: Water and sanitation officer

Answer: yes, there are records on land use and land cover by using Kamonyi land use master plan.

Name: Alphonse Hishamunda

Institution: MINEMA

Position: Ag. Director of Prevention and Mitigation Unit

Answer: I think the National Land Use and Development Master Plan 2020-2050 contains enough information. It can be accessed through google.

5. What are your thoughts on sediment transport and the ecological status of rivers in the area?

Name: Alsaad Ndayizeye
Institution: Rwanda WRB

Position: River Flood Control Specialist

Answer: The sediment transport in the area is high due to the degraded watersheds and river systems. The ecological status of the rivers also was deteriorated due to human activities, including mining activities, unsustainable agriculture, etc, in the area.

Name: NIRAGIRE Ezechiel

Institution: LODA Staff based in Muhanga District

Position: Environmental & Social Safeguards Specialist

Answer: Sediments are transported to rivers by soil water erosion but also some of them are deposited by farmers encroaching buffer zones of rivers during cultivation of land.

The ecological status is that there is some species of fish and other aquatic animals as well as different types of flora.

Name: NZABAHIMANA James

Institution: Kamonyi district

Position: Water and sanitation officer

Answer: The sediment transport and the ecological status on the Nyabarongo catchment and Bakokwe subcatchment is rereferred as , B
is the movement of solid particles (sediment), typically due to a combination of gravity acting on the sediment, and/or the movement of the fluid in which the sediment is entrained. Sediment transport occurs in natural systems Nyabarongo catchment and Bakokwe where the particles are clastic rocks (sand, gravel, boulders, mud, or clay; the fluid is air, water, or ice; and the force of gravity acts to move the particles along the sloping surface on which they are resting. Sediment transport due to fluid motion occurs in rivers and due to currents and tides. Transport is also caused by glaciers as they flow, and on terrestrial surfaces under the influence of wind. Sediment transport due only to gravity can occur on sloping surfaces in general, including hillslopes, scarps and slope boundary.

Name: Alphonse Hishamunda

Institution: MINEMA

Position: Ag. Director of Prevention and Mitigation Unit

Answer: High loads of sediments are evident in the area and rivers do no longer follow their courses/ways. This affects ecological elements of rivers as well.

6. What solutions would you like to implement in order to prevent damage caused by floods?

Name: Alsaad Ndayizeye
Institution: Rwanda WRB

Position: River Flood Control Specialist

Answer: *You can refer to the RWB Strategic Plan which can be found at this link:* https://www.rwb.rw/fileadmin/user_upload/RWRB/Documents/Rwanda_Water_Resources_Board_Strategic_Plan.pdf

Name: NIRAGIRE Ezechiel

Institution: LODA Staff based in Muhanga District

Position: Environmental & Social Safeguards Specialist

Answer: The solution is to implement integrated soil and water management practices, among them include erosion control by constructing terraces, construction of water ways, gully rehabilitation, rain water harvesting techniques, plantation of trees, river bank protection as well as awareness campaign to population on the prevention of flood.

Name: NZABAHIMANA James

Institution: Kamonyi district

Position: Water and sanitation officer

Answer: The solutions we will implement in order to prevent damage caused by floods are rainwater harvesting on residential houses, making radical terraces, tree plantation at hillside, river bank protection grasses & trees plantation, construction of dams and retention ponds.

Name: Alphonse Hishamunda

Institution: MINEMA

Position: Ag. Director of Prevention and Mitigation Unit

Answer: Integrated approach in the catchment including the following: Desiltation/clearing of sediments from river flood plains, improve settlements and livelihoods in the area, relocation of vulnerable households from marginal lands/high risk zones), restoration of degraded lands and rehabilitation of destroyed infrastructures, establishment of anti-erosive trenches as well as progressive and radical terraces, afforestation in the area.

Questions 7-10 can be summarised into table A6 concluding the respondents answers and a calculated mean value. All questions asked search the answers to how likely is it that floods cause the scenarios presented in table A6.

Table A6. The answers to question 7-10. The numbers 1-6 correspond to the following perception: 1 = Not likely, 2 = Possible, 3 = Likely, 4 = Very Likely, 5 = Most Likely, 6 = Certain.

Name	Institution	Reduction in agricultural productivity?	Roads to become impassable/ non-usable?	Loss of human lives?	Damage to house property?
Alsaad Ndayizeye	RWB	5	4	3	5
Niragire Ezechiel	LODA-Muhanga District	4	3	2	1
Nzabahimana James	Kamonyi District	3	2	2	3
Alphonse Hishamunda.	MINEMA	4	3	3	4
	Average:	4 (very likely)	3 (likely)	2.5(possible/likely)	3.25 (likely)