Global Academic and Scientific Journal of Multidisciplinary Studies (GASJMS)
Volume 3 | Issue 2, 2025 Journal Homepage: https://gaspublishers.com/gasjms/ ISSN: 2583-8970
Email: gaspublishers@gmail.com

Assessing the Influence of Nyabarongo River Catchment Characteristics on Flood Risk and Inundation in Rwanda

Jahnuah Voker

University of Lay Adventists of Kigali

Received: 30.04.2025 | **Accepted:** 05.05.2025 | **Published:** 19.05.2025

***Corresponding Author:** Jahnuah Voker

DOI: *10.5281/zenodo.15463281*

Abstract **Original Research Article**

The Nyabarongo River Catchment in Rwanda is highly prone to flooding, posing serious threats to both the environment and nearby communities. This study examined how catchment characteristics influence flood risk and inundation across the region. The main objectives included identifying flood-prone zones, analyzing the extent of flooding, and evaluating how factors like topography, land use, soil, rainfall, and vegetation affect flood vulnerability. A mixed-methods approach was used, integrating geospatial and remote sensing data with field surveys for validation. Tools such as the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS) were employed to map and assess flood risks. The analysis identified five flood risk zones: very high-risk (8.6%) in low-lying areas near rivers; high-risk (21.5%) within 200 meters of rivers affected by rainfall and poor drainage; moderate-risk (31.8%) areas 200–400 meters from rivers; low-risk (34.6%) zones in central and eastern regions with favorable soil and slope conditions; and very low-risk (3.5%) areas with high elevation and well-drained soils. Inundation mapping showed that croplands, wetlands, and built areas near the river were most affected. Key contributors to flood risk included rainfall distribution (22.5%), proximity to streams (16.3%), and land use/cover (15.7%), with urbanization and unsustainable agriculture worsening conditions. The study found strong correlations between catchment features and flood vulnerability. It recommends afforestation, improved urban drainage, and sustainable land management practices to reduce future flood risks. The findings offer crucial insights for integrated flood management strategies, emphasizing the need to address both environmental and human factors in reducing flood impacts.

Keywords: *GIS, Flood, Inundation, Flood Risk, Nyabarongo River Catchment, Remote Sensing, Rwanda*.

Citation: Voker, J. (2025). Assessing the influence of Nyabarongo River catchment characteristics on flood risk and inundation in Rwanda. *Global Academic and Scientific Journal of Multidisciplinary Studies*, *3*(2), 56-70.

1. INTRODUCTON

Flooding ranks among the most destructive natural disasters, impacting hundreds of millions of people around the world each year (Liu, 2024). Each year, floods claim the lives of an estimated 6,000 to 18,000 people, with India accounting for roughly 20% of these deaths. In 2022, India recorded the highest number of flood-related fatalities globally, with approximately 2,100 deaths, while Pakistan reported over 1,700. Overall, Asia bore the brunt of flood mortality that year, contributing nearly two-thirds of the global total with around 4,800 deaths. This figure surpassed the continent's average annual flood death toll over the previous decade, which stood at approximately 3,700 (Yari et al., 2020).
As of 2022, the Republic of Congo had the highest flood risk in Africa, followed by Egypt, Nigeria, and Sudan, all scoring eight or more on a 0–10 risk index measuring annual flood exposure (Statista, 2024). Most African countries scored above 4.1, indicating widespread vulnerability. That year, floods affected around 1.5 million people across the continent, marking some of the worst events in decades (Africa News, 2023). In Rwanda, torrential rains in the northwest caused at least 15 deaths, extensive infrastructure damage, and displaced 7,000 people across 10 villages (OCHA, 2023).

Between April 30 and May 4, 2022, heavy rains and floods in Rwanda caused 14 deaths in Nyanza District, injured 27 people in Burera District, and damaged roads, bridges, and 123 houses (OCHA, 2024a). The Rwanda Meteorology Agency had forecasted rainfall of 40–50 mm across 17 districts, but Burera, Nyanza, Gakenke, and Ngororero received 84–105.2 mm, triggering severe flooding, landslides, and infrastructure damage. In early May 2022, over 130 people died due to catastrophic flooding, particularly in the Northern and Western provinces, including Ngororero, Rubavu, Nyabihu, Rutsiro, and Karongi (Kawera, 2024). Again, in early May 2024, floods and landslides devastated Rwanda's northern, western, and southern provinces, killing 131 people and displacing more than 5,800 families. The disaster destroyed 6,391 homes, damaged schools, health centres, power stations, and key infrastructure, while also sweeping away crops and livestock (Relief web, 2024). The Nyabarongo River catchment, Rwanda's largest, is especially prone to rapid flooding after prolonged rainfall, causing severe property damage and disrupting socio-economic activities (Mind'je et al., 2021a) This study aims to evaluate flood risk and inundation extent as influenced by the characteristics of the Nyabarongo River catchment in Rwanda. Filling this research gap is vital for understanding how the catchment responds to climatic variables and for informing effective catchment planning and early flood warning systems. By offering new insights into flood dynamics within this key watershed, the research builds on previous studies and supports improved disaster management and mitigation strategies in Rwanda and comparable regions.

1.2. STATEMENT PROBLEM

The Nyabarongo River catchment in Rwanda is a vital water resource supporting both ecological balance and economic development (Nsengimana et al., 2017). However, the area faces increasing flood risks, largely driven by specific catchment characteristics (Manikuze, 2021). These floods pose serious threats to human settlements, agricultural activities, and infrastructure (Sugianto et al., 2022a). The flooding is primarily caused by the catchment's rapid hydrological response to prolonged rainfall, often resulting in riverbank overflow and floodplain inundation (El-Bagoury & Gad, 2024). For example, during the long rainy season from March to May, the Rwanda Water Resources Board (RWB) issued warnings about potential flooding from rivers such as the Sebeya, Karambo, Nyabahanga, Kabirizi, Nyabarongo, and others in the Virunga Corridor. In particular, the Nyabarongo River's overflow in early May 2023 was a key driver of widespread flooding due to its quick hydrological reaction to sustained heavy rains. Despite the urgent need, there remains a lack of comprehensive studies examining how factors such as land use change, soil properties, topography, and climate variability contribute to flood risk in the catchment (Kwisanga, 2017; Zhang et al., 2018).

1.3. OBJECTIVES OF THE STUDY

1.3.1. General Objective

The general objective of this research is to assess the influences of Nyabarongo River catchment characteristics on Flood risk and inundation in Rwanda from 2014 to 2023.

.

1.3.2. Specific Objectives

I. To identify and demarcate flood risk zones across the Nyabarongo River Catchment in Rwanda.

II. To determine and map inundation extent for the identified high-risk zones across the Nyabarongo River Catchment in Rwanda.

III. To assess the catchment's characteristics mainly influencing flood risk across the Nyabarongo River Catchment in Rwanda.

IV. To examine the relationship between the catchment's characteristics and flood risk across the Nyabarongo River Catchment in Rwanda.

1.3.3. Research Questions

I. What are the specific flood risk zones across the Nyabarongo River Catchment?

II. To what extent has the catchment been inundated in the identified high-risk zones across the Nyabarongo River catchment?

III. What are the main driving factors influencing flood risk and inundation extent across the Nyabarongo River catchment?

IV. What is the relationship between the catchment's characteristics and flood risk across the Nyabarongo River catchment?

2.0. REVIEW OF LITERATURE

A theoretical review or framework within academic research entails a critical evaluation and integration of established theories, models, and conceptual frameworks pertinent to the research topic or question. It involves examining and discussing key theoretical perspectives and related concepts that contribute to a deeper understanding of the phenomenon being studied. Presented below is a summary of the selected theories, models, and frameworks that informed and guided this research.

2.1. THEORETICAL REVIEW

2.1.1. Social Risks Theory

The concept of risk, as introduced by O'Keefe, Westgate, and Wisner in the 1970s, redefined natural disasters by emphasizing their socio-economic dimensions, arguing that such events are not solely natural but are significantly shaped by human vulnerability and inequality (Fineman, 2019). This perspective laid the groundwork for Social Risk Theory, which has become central in understanding and managing flood and inundation risks. The theory posits those social conditions such as poverty, marginalization, and lack of access to resources interact with physical hazards to amplify disaster impacts.

In the context of this study, which assesses flood risk and inundation extent in the Nyabarongo River Catchment in Rwanda, Social Risk Theory serves as a crucial analytical lens. The research applied this theory to identify and map high-risk flood zones within the catchment, integrating physical characteristics like topography, land use, and hydrological response with socio-economic vulnerability factors. As Filianoti et al. (2020) highlight, understanding floods requires more than hydrological analysis it demands consideration of how social systems influence exposure and resilience.

By embedding Social Risk Theory into the assessment framework, this study provides a holistic view of flood risk that accounts for both environmental and social drivers. It supports the development of inclusive flood management strategies that prioritize the needs of vulnerable communities and promote equitable risk reduction (Kwisanga, 2017b). This approach not only enhances disaster preparedness but also contributes to sustainable and just climate adaptation planning.

2.1.2. Environmental Justice Theory

Environmental justice theory, developed by Robert Bullard, Paul Mohai, Robin Saha, and Beverly Wright in the 1980s, addresses the unequal distribution of environmental burdens and benefits, particularly focusing on marginalized communities (Menton et al., 2020). The theory emerged from social movements advocating for the fair distribution of environmental risks and resources, emphasizing community rights and participation in decision-making processes (Beretta, 2012). It integrates environmental concerns with social equity, aiming to reduce disparities and empower affected populations in environmental governance. In flood risk and inundation management, environmental justice principles call for inclusive strategies that consider the disproportionate impacts of flooding on vulnerable populations, including socioeconomically disadvantaged groups living in informal settlements or low-lying areas (Nyam & Modiba, 2024). By applying environmental justice frameworks, policymakers and researchers can identify and address these inequalities, ensuring flood management strategies prioritize equitable outcomes and enhance community resilience (Nkurunziza, 2022).

2.2. CONCEPTUAL REVIEW

2.2.1. Topography

The Nyabarongo River, Rwanda's longest river, originates from the northern highlands, flowing southward, then turning west and north before joining the Nile River system. The topography of the Nyabarongo River catchment is highly varied, featuring rugged mountains, steep hills, rolling plains, and wetlands (Wali et al., 2020). Elevations within the catchment range from approximately 1,300 meters in the lowland valleys to over 2,900 meters in the mountainous regions, such as the Virunga Volcanoes and the Congo-Nile Divide (Nsengiyumva et al., 2018).

The upper catchment areas are characterized by steep slopes and highlands, which contribute to rapid surface runoff, soil erosion, and landslides, particularly during heavy rainfall (Niyonzima & Gasirabo, 2021). These steep terrains lead to the river's swift flow in its upper reaches, where it cuts through narrow valleys and gorges. As the river flows southward and toward the central parts of Rwanda, the landscape gradually shifts to gentler slopes and wide floodplains, especially around the Nyabarongo wetlands (Bizimana & Schilling, 2021).

2.2.2. Vegetation Condition

The vegetation in the Nyabarongo River catchment is diverse, influenced by altitude, soil type, land use, and human activity. Historically, the region was dominated by dense forests, montane vegetation, and wetlands. However, much of the natural landscape has been significantly altered by agriculture, urbanization, and infrastructure development. Remnants of montane and bamboo forests remain in fragmented patches, primarily along the Congo-Nile Divide, with protected areas like Nyungwe National Park preserving some of the last intact ecosystems.

In contrast, the middle and lower reaches of the catchment have largely transformed into agricultural and urban areas. Wetlands along the river, once abundant with papyrus and sedges, face increasing threats from agricultural reclamation, which is disrupting the delicate ecosystem balance (Niyonzima & Gasirabo, 2021).

2.2.3. Land Use and Land Cover

Land use and land cover (LULC) changes within the Nyabarongo catchment have intensified flood risks. Rapid urbanization, wetland reclamation, and agricultural expansion have led to a reduction in permeable surfaces, increasing the vulnerability of the catchment to flooding (Bizoza & Rutikanga, 2018). Urban centers such as Kigali, which partially falls within the Nyabarongo basin, contribute large volumes of storm water runoff. Additionally, the conversion of wetlands, traditionally natural buffers for floods, into farmland has significantly diminished their capacity to absorb floodwaters, leading to more frequent inundations downstream.

2.2.4. Climate Change

Climate change has intensified the hydrological cycle within the Nyabarongo River catchment, leading to more erratic and intense rainfall events. Studies project an increase in extreme weather events, including heavier rainfall during the wet seasons, which elevates the likelihood of floods (MINIRENA, 2015). Rising temperatures also impact evapotranspiration rates and soil moisture retention, further complicating flood management efforts. Without adaptive land and water management strategies, climate-induced changes are expected to amplify the already high flood risks faced by communities along the Nyabarongo River.

2.2.5. Flood Risk and Inundation Extent

Flood risk and inundation extent are influenced by hydrological processes, climate conditions, and human activities (Banjara et al., 2024). These factors collectively determine the frequency, intensity, and spatial distribution of flood events (Xu et al., 2022). Flood risk refers to the likelihood of flooding occurring in a given area and the potential consequences, influenced by rainfall intensity, soil saturation, river capacity, and land use (Koralay & Kara, 2024). Intense or

prolonged precipitation can overwhelm the soil's infiltration capacity, leading to excessive surface runoff. When river channels reach their limits, water overflows into adjacent areas, resulting in inundation. Urban infrastructure, with its impermeable surfaces, further exacerbates flood risks by reducing natural absorption and increasing runoff volumes.
Inundation extent refers to the geographic area affected by floodwaters (Sarchani et al., 2020). It is influenced by topography, drainage infrastructure, and the presence of natural or artificial barriers. Low-lying areas with poor drainage are especially vulnerable to widespread flooding, while steep terrain can lead to flash floods that rapidly spread floodwaters downstream. Additionally, poorly maintained or insufficient drainage systems contribute to prolonged water retention, exacerbating flood impacts.

2.3. EMPERICAL REVIEW

The study by Samarasinghe et al. (2021) aimed to assess flood inundation in the tidal-influenced Kelani River in Sri Lanka, utilizing both 1-D and 2-D hydrodynamic models with HEC-RAS, supported by ground observations and remote sensing. The objective was to generate a flood hazard map for the lower Kelani River basin under various return periods. Discharges were estimated using the HEC-HMS hydrological model, which incorporated updated intensity-depth frequency curves. The simulated flood extent was validated with Sentinel 1 imagery and field surveys, while the models were further validated against observed stage and discharge measurements. The hydrodynamic model achieved high accuracy in simulating inundation extent, with a Nash-Sutcliffe coefficient of 0.90, Pearson correlation of 0.95, and a Success Index of 0.90. The hydrological model also performed well, with a Nash-Sutcliffe coefficient of 0.91 and Pearson correlation of 0.93. The study concluded that the developed flood risk zoning offers a valuable benchmark for the design and implementation of flood control and mitigation measures in the Kelani River basin.
Kelly & Kuleshov (2022) assessed flood hazard risk in the Hawkesbury-Nepean catchment (HNC) using an indicator-based method, developing a Flood Hazard Index (FHI) based on three indicators: maximum 3-day precipitation (M3DP), distance to river-elevation weighted (DREW), and soil moisture (SM). The study, using the March 2021 flood event as a case study, found that nearly 85% of the HNC experienced 'severe' or 'extreme' flood hazard levels, with the central-east urbanized floodplain having the highest FHI values.
The study of Koralay & Kara (2024) focused on the Söğütlü stream watershed in Turkey's Eastern Black Sea Region, aiming to generate a flood risk map using the Analytical Hierarchy Process (AHP) and Weighted Overlay tools in ArcGIS. Key factors such as soil type, rainfall, land use, slope, aspect, elevation, and distance to the stream were used in the analysis. The resulting flood risk map classified the watershed into five risk zones: very high, high, moderate, low, and very low. Statistical analysis showed that low and moderate risk areas covered 95.98% of the watershed, while high and very high-risk zones accounted for 4.02%. Areas near rivers and with low slope and elevation were found to be more prone to flooding. This study is crucial for developing preventive and response strategies, offering insights into flood management and watershed planning. The flood risk map enables planners to implement soil and water conservation measures and better prepare for potential flood events.

2.4. RESEARCH GAP

The existing literature on flood risk assessment and inundation extent provides important insights but also reveals key gaps that need further exploration, particularly in the Nyabarongo River catchment in Rwanda. One major gap is the lack of a detailed analysis that examines how the unique characteristics of the Nyabarongo River catchment influence flood risk and inundation extent locally, as most studies have focused on broader national or regional scales without addressing the specific hydrological and geographic features of this area.
Furthermore, there is a gap in integrating socio-economic factors into flood risk assessments, with many studies primarily focusing on physical and hydrological aspects. Addressing this gap is crucial for developing comprehensive flood risk management strategies that incorporate community vulnerability and resilience. This research aims to fill these gaps by using spatial analysis, socio-economic indicators, and advanced statistical modeling, contributing to a better understanding of flood risk and inundation in the Nyabarongo River catchment and enhancing flood management and community resilience strategies in the region.

Social-Ecological Systems (SES) Framework

The ecological system of a river includes its natural environment, such as water quality and the services it provides, like drinking water, fishing, and recreation, as well as factors that impair its health, such as pollution or habitat destruction. This system is monitored through indicators that assess the river's health. The social system, made up of human communities relying on and interacting with the river, is shaped by factors like socio-demographics, economic capacity, food security, and health, as well as people's ability and motivation to protect the river. Human decisions, such as policy-making, management actions, and conservation efforts, impact the ecological system and its health. This creates a dynamic, reciprocal relationship where nature influences people through its benefits, and people influence nature through their choices, resulting in an ongoing, interconnected exchange between both systems (McGinnis & Ostrom, 2014).

Figure1: Social-ecological systems (SES) framework

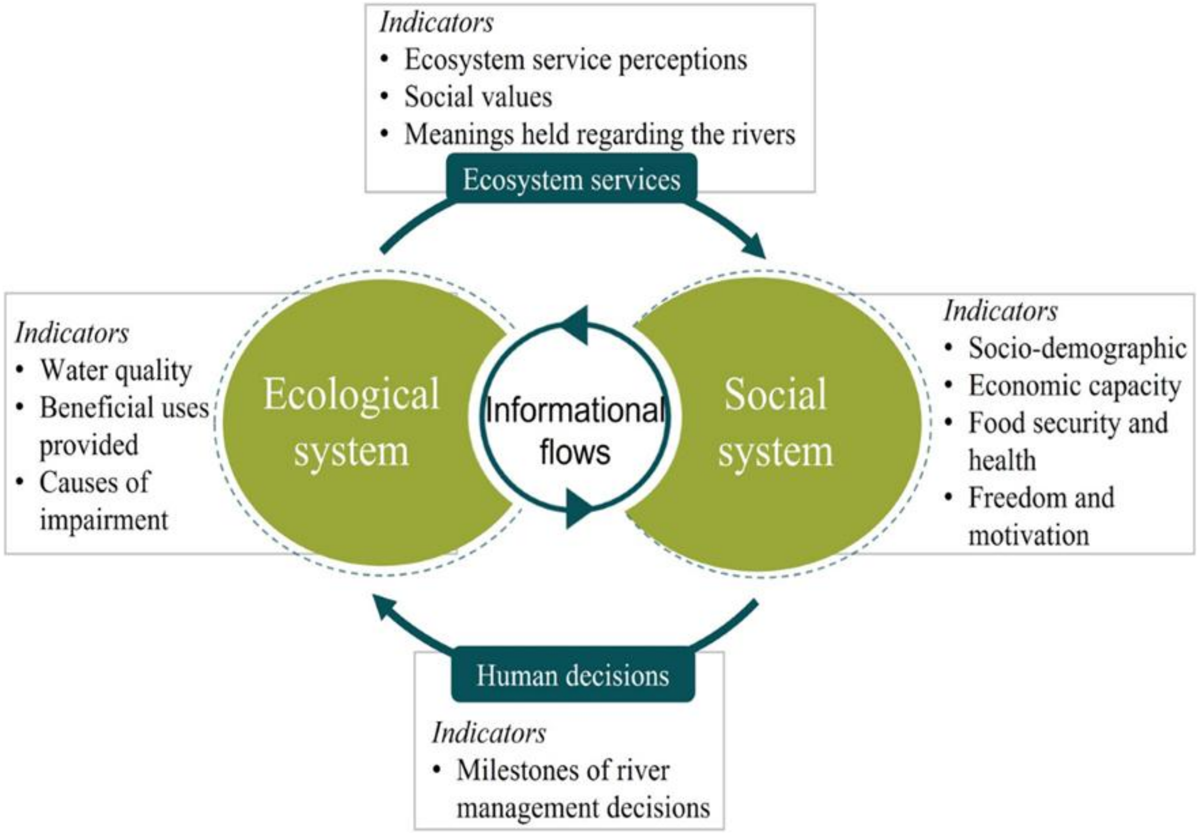
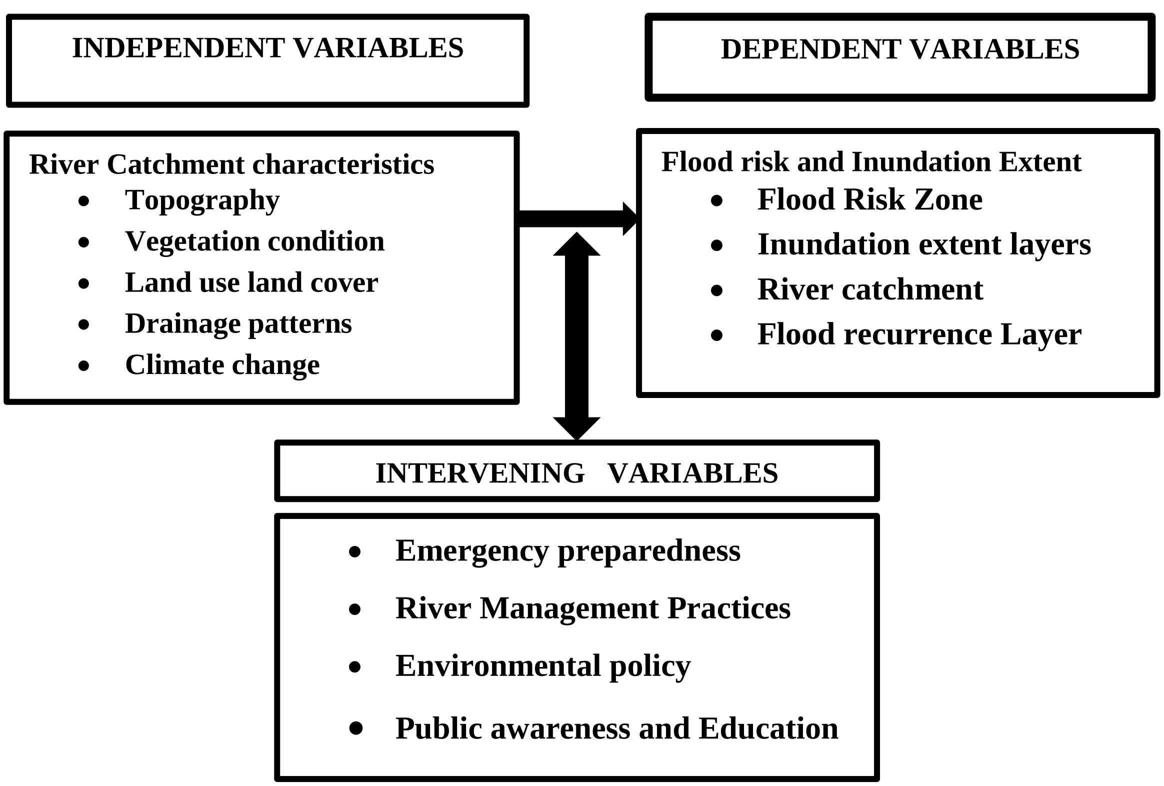


Figure 2: Conceptual Framework



3.0. MATERIALS AND METHOD

3.1. Research Design

This research employed a cross-sectional quantitative and qualitative design to assess the flood risk and inundation extent influenced by the characteristics of the Nyabarongo River Catchment in Rwanda. The study began with a data collection phase that included obtaining administrative and raster data from satellite images, which were crucial in examining the multifaceted impacts of flood risk and inundation. Quantitative methods, particularly the analysis of satellite imagery, provided numerical data that helped explore the relationship between flood risk, inundation, and the catchment's characteristics. The findings were used to identify key factors driving flood risks and inundation extent, informing strategies for effective flood management and mitigation in the region. The research design ensured a thorough and objective examination of the flood risks in the Nyabarongo River Catchment.

3.2. Area of the Study Physical Presentation

Rwanda, a landlocked country endowed with abundant water resources, is home to an intricate network of rivers, lakes, and wetlands (DCIF, 2022). The country is divided into two major hydrological basins by the Congo-Nile divide, with the eastern side falling under the Nile Basin, which includes the Akagera and Nyabarongo river catchments. The Nyabarongo catchment, covering 8,478 km², spans all four provinces, including the capital, Kigali. It is divided into an upper catchment, characterized by high altitudes, steep slopes, and dense tributary networks, and a lower catchment with tributaries like the Bakokwe and Mukungwa rivers. The catchment's diverse topography results in significant weather variability, with elevations ranging from 1,332 m to 4,480 m above sea level (Karamage et al., 2016b).

Figure 3: study area map

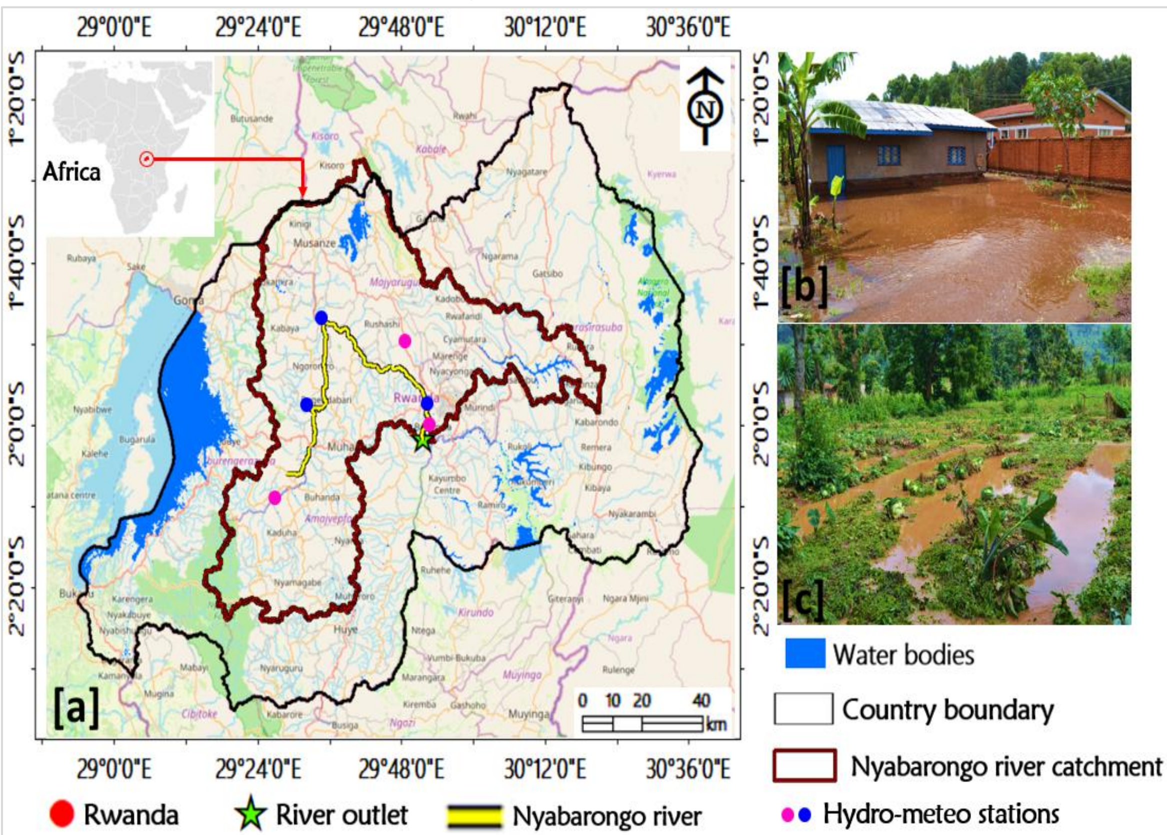


Figure 3: Geographic location map of the Nyabarongo River basin; [a] the basin and its extent within Rwanda (the base map sourced from ArcMap utilizing Open Street Map data) with a red dot indicating the location of Rwanda in Africa; [b] and [c] the occurrence of flooding resulting from the overflow of the Nyabarongo River and inundated area (Source: author's captured photographs).

3.5. DATA QUALITY CONTROL

This part of the third chapter will present the data quality control through the validity and reliability.

3.5.1. PRIMARY DATA

To complement the secondary datasets, this research incorporated observational methods to gather primary data for ground-trothing, ensuring a nuanced understanding of the local context. Field observations were conducted across the Nyabarongo River catchment to capture the physical landscape, infrastructure and settlement patterns that can be inundated. Structured visits were made to targeted areas, systematically documenting relevant features. Photographic and video documentation accompanied these observations, aiding in data analysis.

Triangulating primary field data with secondary datasets provided a comprehensive understanding of flood risks and characteristic of Nyabarongo River. The Nyabarongo River's flow dynamics and extensive floodplains, influenced by its numerous tributaries and varying topography.

3.5.2. Secondary Data

The data for this study included geospatial datasets, remote sensing techniques, topographic maps, and climate and hydrological data, complemented by aerial photographs. High-resolution satellite imagery from providers like NASA and the USGS was used for detailed analysis of the Nyabarongo River catchment. Landsat imagery and digital elevation models assessed topographic and hydrologic factors, along with vegetation and surface characteristics influencing flood risks. Key factors considered in the study included elevation, slope gradient, aspect, flow direction, flow accumulation, proximity to rivers, Topographic Wetness Index (TWI), Stream Power Index (SPI), Normalized Difference Vegetation Index (NDVI), land use/land cover (LULC), soil types, and rainfall, all contributing to a comprehensive evaluation of flood risks and inundation in the catchment.

3.5.3. Data Processing

Data for evaluating flood risk and inundation in the Nyabarongo River catchment were collected through a combination of field surveys and remote sensing. Field surveys provided on-the-ground data, while satellite imagery and high-resolution Digital Elevation Models (DEMs) supplied crucial spatial data. Geological and historical flood data were sourced from government agencies and literature. High-resolution Sentinel-1 imagery was used to precisely delineate flood extents. Additionally, qualitative data, including expert opinions, historical records, photographs, and field observations, were used to validate the findings and enhance understanding of local flood dynamics.

3.5.4. Data Analysis

The data processing and analysis combined the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS) to identify flood-vulnerable areas in the Nyabarongo River catchment, using expert-driven evaluations and spatial data to generate flood risk zones for community-based resilience planning.

3.6. ETHICAL CONSIDERATION

Before analyzing flood risk and inundation data in the Nyabarongo River catchment using secondary data like GIS and imagery, ethical considerations were strictly followed. The researcher obtained permission from relevant authorities, such as REMA, with an introduction letter from UNILAK University. Ethical measures included ensuring that all data were legally sourced, respecting intellectual property rights, and maintaining confidentiality. Data from GIS datasets and remote sensing imagery were used only for research purposes, with strict efforts to prevent unauthorized access. The researcher adhered to data sharing agreements and licensing terms to ensure responsible and ethical use of geospatial data.

3.7. POST ESTIMATION TESTS

This study may face several limitations, including language barriers during interactions with local communities and authorities, which could affect data collection and interpretation. Hiring local translators or interpreters could mitigate this. Biases in data collection methods, such as field surveys and remote sensing, may impact accuracy; rigorous training and standardized protocols can minimize this. Relying on secondary data may introduce limitations in data quality and timeliness, which can be addressed by validating and cross-referencing data and incorporating primary data collection. Acknowledging these limitations transparently in the methodology and findings enhances credibility, and adapting methodologies based on emerging challenges can further overcome these issues.

4.0. RESULTS AND DISCUSSIONS OF FINDINGS

4.1. Flood Risk Zones across the Nyabarongo River Catchment (2014 To 2023)

The flood risk map of the Nyabarongo River catchment (2014–2023) classifies the area into five zones: very high, high, moderate, low, and very low risk. High-risk zones are mainly located in the western and southwestern parts, close to water bodies and characterized by high rainfall and elevated terrain, making them highly vulnerable to river overflow. These areas, especially near the Nyabarongo River and its tributaries, require structural interventions like floodwalls and levees. High-risk zones also extend to the central and southern parts, where moderate slopes and poor water infiltration increase flood susceptibility. Moderate-risk areas, located in the central and eastern parts, benefit from natural protection from terrain and vegetation, offering some flood mitigation. Low and very low-risk areas are found predominantly in the eastern parts of the catchment.

Figure 4: Flood risk Zones

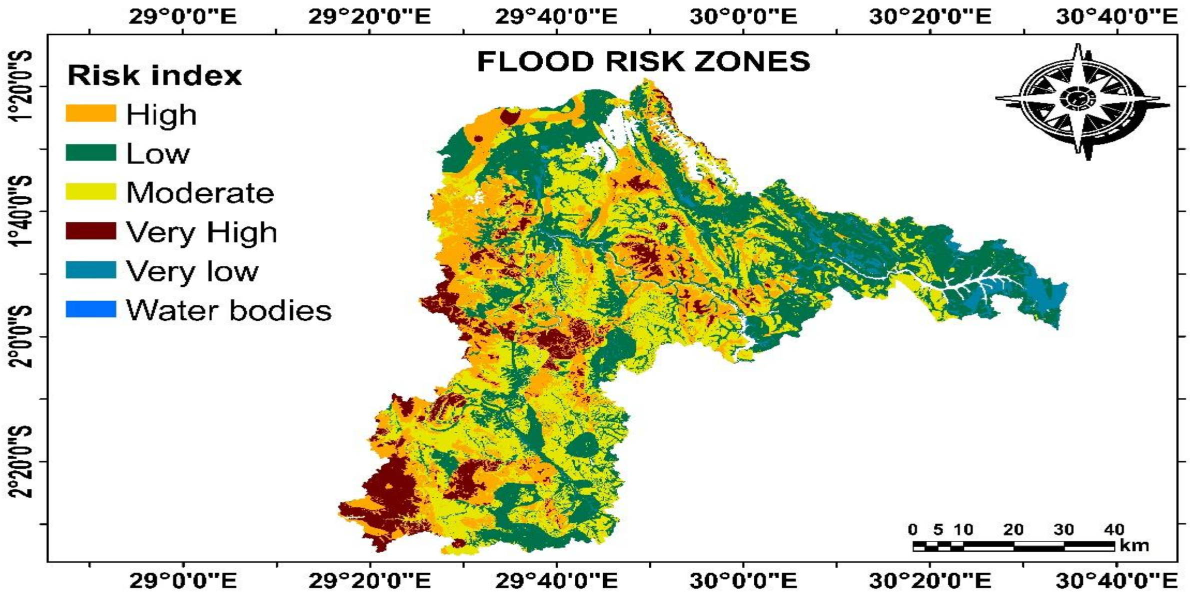


Figure 4 illustrates the flood risk assessment of the Nyabarongo River catchment, revealing a significant distribution of flood-prone areas. Specifically, 8.6% of the catchment is categorized as very high risk, and 21.5% as high risk. Moderate risk areas account for 31.8%, while 34.6% is considered low risk, and only 3.5% falls under very low risk. The cumulative percentage of moderate to very high-risk zones, totaling 61.9%, underscores the significant flood vulnerability in the catchment. With 30.1% of the catchment in high and very high-risk categories, immediate intervention is needed to protect communities and infrastructure. The limited area of very low-risk zones highlights the catchment's overall susceptibility to flooding, emphasizing the need for comprehensive flood resilience planning, including both structural and non-structural measures to mitigate risks and protect livelihoods and the environment. The findings stress the importance of proactive and sustained flood management efforts to ensure long-term resilience in the catchment.

Figure 4.1: Percentages per flood risk class

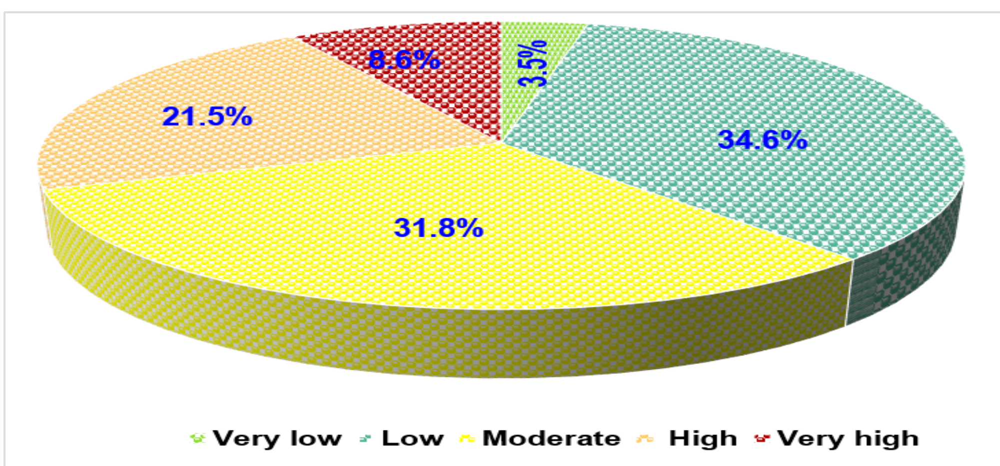
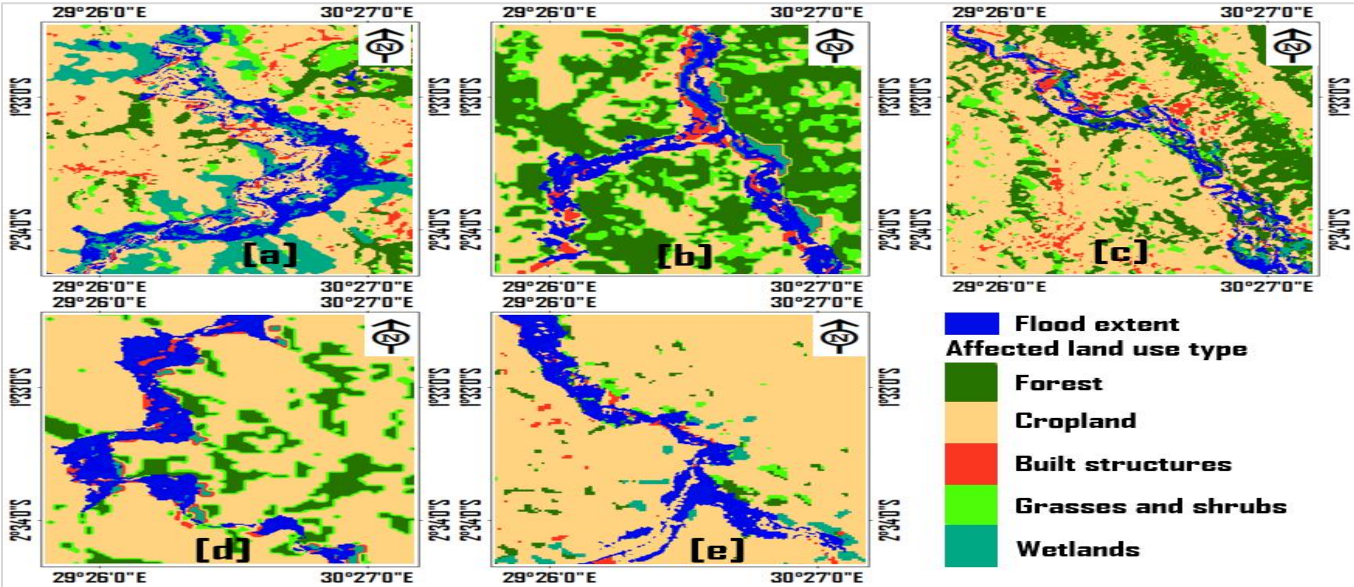


Figure 4.1 shows that from 2014 to 2023, flood events in the Nyabarongo catchment increased significantly, with extreme rainfall events exceeding 114% of the norm, rapid urbanization, deforestation, and poor farming practices increasing flood risks, particularly in high-risk zones, where croplands, wetlands, and built structures were most vulnerable, with a need for targeted mitigation strategies to preserve natural buffers and improve infrastructure.

Figure 4.2.: Inundation extent layers ((2014–2023)



The inundation extent layers integrated with land cover data for reported districts at risk. [a] Nyarugenge and Kamonyi, [b] Ngororero and Muhanga, [c] Rulindo district, [d] Karongi and Ruhango, [e] Nyamagabe and Nyanza

Figure 4.3.: Catchment characteristics mainly influencing flood risk across the Nyabarongo River catchment (2014 to 2023)

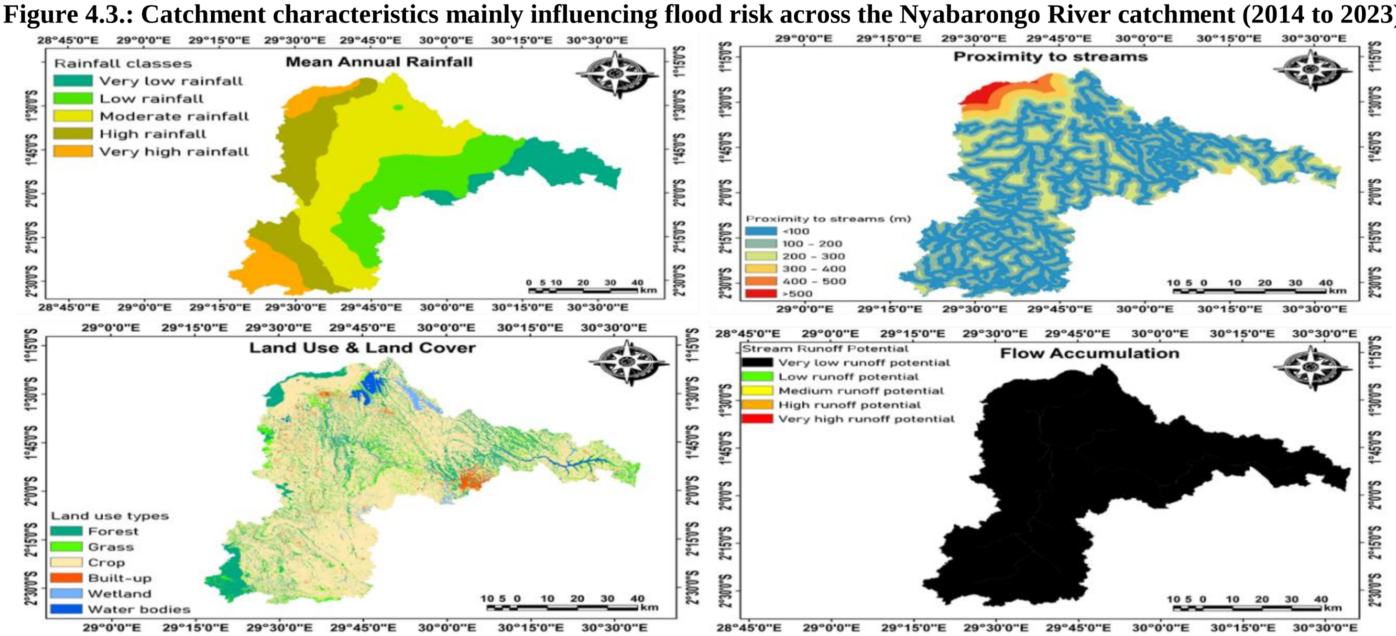


Figure 4.3 identifies rainfall (22.5%), proximity to streams (16.3%), land use/land cover (LULC) (15.7%), and flow accumulation (12.6%) as the key factors driving flood risk in the Nyabarongo catchment, with very high rainfall, areas near water bodies, impervious surfaces, and poor drainage systems contributing significantly to flood vulnerability, highlighting the interconnected roles of these factors in shaping flood risks.

Table 1. Indicates the relationship between catchment characteristics and influencing factors of flood risk in the Nyabarongo River catchment highlighting the complexities of flood dynamics.

Factors	Facc	Elev	LULC	Spr	SPI	Pstr	TWI	Slope	STI	Rfall	Rate (%)	Rank
Facc	1	0.11	1	6	3	0.5	2	5	5	0.33	12.6	4
Elev	0.5	1	0.33	5	0.5	0.5	1	9	2	0.11	6.5	6
LULC	1	9	1	9	1	1	3	7	7	1	15.7	3
Spr	0.2	1	0.14	1	0.2	0.13	9	5	2	0.14	6.1	8
SPI	0.33	7	1	9	1	1	2	5	7	0.33	11.5	5
Pstr	2	9	1	7	1	1	2	5	7	0.5	16.3	2
TWI	7	0.2	0.11	1	0.14	0.14	1	0.5	0.33	0.11	1.8	9
Slope	0.2	7	0.14	0.5	0.2	0.2	0.5	1	0.33	0.11	6.2	7
STI	0.17	5	0.11	3	0.11	0.14	0.2	0.2	1	0.11	1.6	10
Rfall	3	9	1	9	3	2	9	7	9	1	22.5	1

Mostly influencing | Moderately influencing | Least influencing | identity matrix

Table 1 show that Facc: Flow accumulation, **Elev:** Elevation, **Spr:** Soil properties, **SPI:** Stream Power Index, **Pstr:** Proximity to streams, **TWI:** Topographic Wetness Index, **STI:** Sediment Transport Index, **Rfall:** Rainfall

Figure 4.5 shows that the Stream Power Index (SPI), elevation, slope, and soil properties contribute moderately to flood risk across the Nyabarongo catchment. SPI, with an 11.5% contribution, indicates higher flood risks in regions with greater stream erosion and altered stream geometry. Elevation (6.5%) and slope (6.2%) influence water flow, with low-lying areas prone to flooding and steep slopes increasing runoff. Soil properties (6.1%) affect infiltration rates, with poorly draining soils exacerbating runoff and increasing flood potential, especially during heavy rainfall.

Figure 4. 4. Moderately influencing factors of flood across the Nyabarongo River catchment (2014 to 2023)

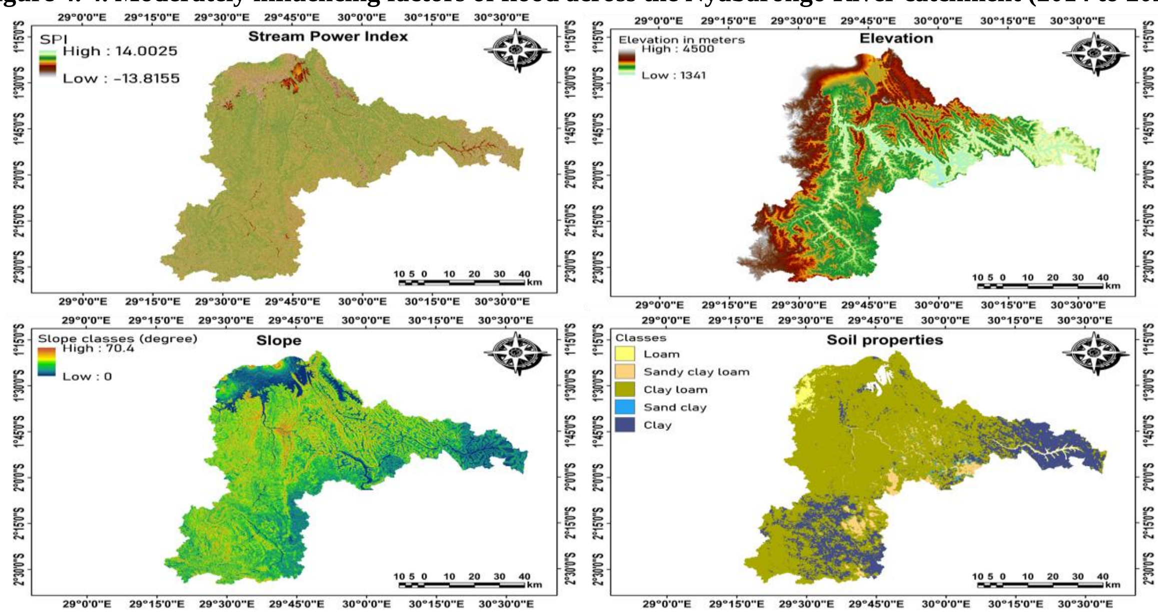


Figure 4.4 shows that the Topographic Wetness Index (TWI) and Sediment Transport Index (STI) contribute minimally to flood risk, with rates of 1.8% and 1.6%, respectively, but still play important roles; TWI identifies areas with higher water retention, increasing saturation and flood risk, while STI highlights sediment movement, which can reduce drainage and exacerbate runoff. High TWI values in the central, southern, and eastern areas indicate higher saturation risks, while low TWI areas in the north and west suggest better drainage. High STI values in the southern and eastern regions indicate greater sediment transport, further reducing drainage and heightening flood risks.

Figure 4. 5. Least influencing factors of flood across the Nyabarongo river catchment

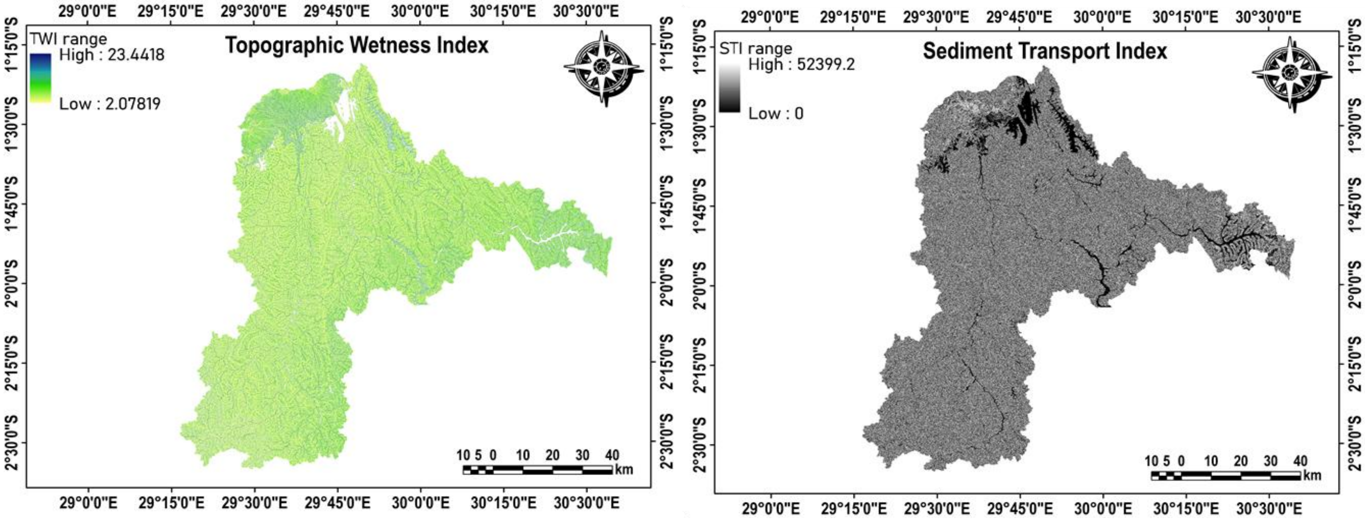
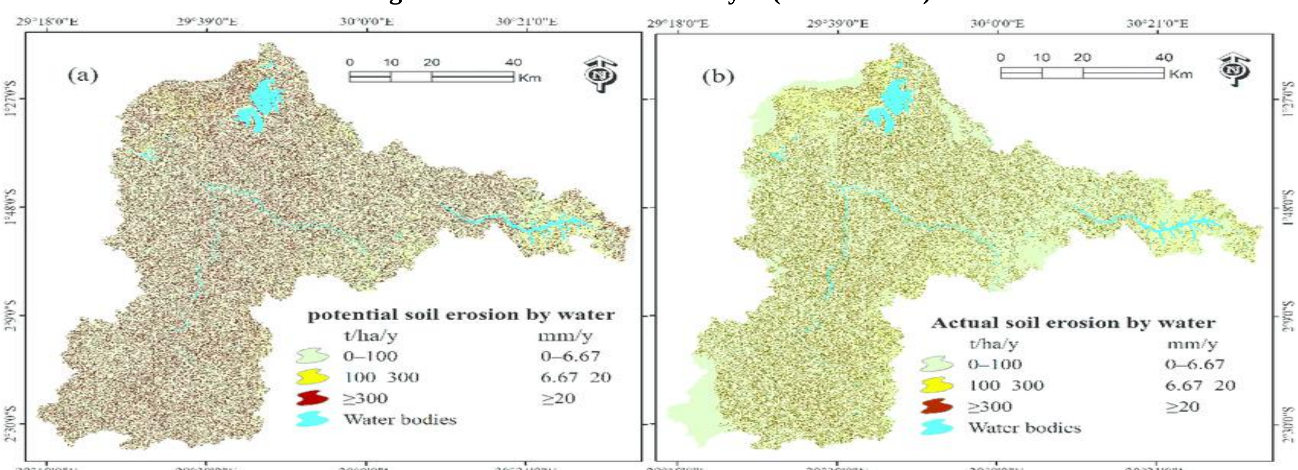


Figure 4.5 shows that the flood risk assessment of the Nyabarongo River catchment confirms that rainfall, proximity to streams, land use/land cover (LULC), slope, and elevation are critical factors influencing flood vulnerability, consistent with previous studies. Research by Samarasinghe et al. (2021) and Kelly and Kuleshov (2022) supports the finding that areas near water bodies and regions with heavy rainfall are most flood-prone, with rainfall being the primary flood driver in Nyabarongo (22.5% contribution). The study emphasizes the need for structural flood mitigation in the central and southern zones, supports Koralay and Kara (2024) on the role of urbanization and agriculture in exacerbating runoff, and highlights slope-specific interventions, aligning with Nguyen et al. (2021) on the vulnerability of low-lying and steep slope areas. Additionally, the role of proximity to streams, as detailed by Stein et al. (2021b), was validated in the Nyabarongo catchment, where areas within 100 meters of water bodies are highly vulnerable to rapid flooding during heavy rains. This supports the recommendation for implementing early warning systems, embankments, and floodplain zoning to enhance community resilience. Overall, the comprehensive flood risk analysis for the Nyabarongo River catchment provided a detailed spatial understanding of flood dynamics, illustrating the critical interplay of rainfall, land use, elevation, and proximity to water bodies in shaping flood vulnerability across the landscape.

Figure 4.6. Flood recurrence Layer (2014 to 2023)



Soil Loss (t/ha/year)	Erosion Rate (mm/year)	Colour on Map	Meaning
0–100	0–6.67	Light Green	**Low soil erosion**: Land is relatively stable; minimal soil is being washed away by water. This usually represents areas with good vegetation cover, conservation measures, or gentle slopes
100–300	6.67–20	Yellow	**Moderate soil erosion**: Noticeable soil loss is happening. It may start affecting agriculture, reduce soil fertility, and contribute sediment to rivers. Often found in areas with farming on slopes or degraded land.
>300	>20	Red	**Severe soil erosion**: A high amount of soil is being lost annually. These are danger zones where land degradation is critical — leading to loss of arable land, river siltation, landslides, and higher flood risk. Immediate soil conservation actions are needed here.
Water Bodies	—	Light Blue	**Lakes, rivers, wetlands**: Natural water bodies with no soil erosion measured (since its water, not land). They act as storage or movement channels for runoff and eroded materials.

5.0. SUMMARY OF KEYS FINDINGS

Summary of Findings

The Nyabarongo River catchment, Rwanda's largest river system, has faced increasing flood risks and inundation events between 2014 and 2023, driven by both natural and human-induced factors. Key contributors include topography, land use changes, rainfall variability, and the broader impacts of climate change. Notably, extreme rainfall anomalies occurred in 2018, 2020, and 2022, with rainfall levels soaring up to 146% above normal, leading to widespread flooding and significant damages across the catchment.

The Lower Nyabarongo Catchment, covering 3,304 km² and receiving about 1,200 mm of rainfall annually, experiences substantial surface water flow (around 28 m³/s). Predominantly characterized by rain-fed agriculture and rapid urban development, particularly in Kigali, the region remains vulnerable due to limited erosion control measures.

The catchment's demographic pressure further exacerbates flood risks. According to the 2012 population census, the total population within the catchment was approximately 2.18 million, with the highest densities observed in Kigali and surrounding urban centers like Gicumbi, Muhanga, and Rwamagana. This concentration of people and infrastructure, especially in flood-prone zones, increases the region's vulnerability to flood events. The 2012 census figures were slightly lower (4.39%) than the low-growth scenario projections, but they still highlight significant population pressures that must be considered in future flood management and urban planning efforts.

Overall, the findings underscore the complex interplay of climatic, geographic, and human factors in shaping the Nyabarongo catchment's flood risk profile. They emphasize the urgent need for integrated flood risk management strategies, including better land use planning, strengthened erosion control measures, investment in flood resilience infrastructure, and climate adaptation initiatives to safeguard livelihoods and infrastructure across the catchment.

5.1. Objective One: To Assess and Demarcate Flood Risk Zones across the Nyabarongo River Catchment in Rwanda

The study aimed to assess and delineate flood risk zones across the Nyabarongo River Catchment, categorizing the area into five levels of vulnerability. Very high-risk zones (8.6%) are concentrated near water bodies in the western and southwestern regions, where the terrain and proximity to rivers heighten flood susceptibility. High-risk zones (21.5%) are mostly found in the central and southern parts of the catchment, characterized by moderate slopes and inadequate drainage. Moderate-risk zones (31.8%) lie between 200-400 meters from rivers and offer partial resilience but remain vulnerable during heavy rainfall. Meanwhile, low-risk (34.6%) and very low-risk (3.5%) zones are mainly located in the central, eastern, and southeastern regions, benefiting from better elevation, terrain, and soil drainage conditions. Overall, the findings show that 61.9% of the Nyabarongo catchment falls within moderate to very high flood risk zones, largely concentrated near rivers in the western, central, and southern areas. The combination of close proximity to water bodies, gentle slopes, and insufficient drainage systems significantly increases the vulnerability of these regions. This spatial risk pattern highlights the urgent need for targeted flood mitigation strategies, particularly in the highest-risk zones, to reduce the impacts of future flooding events and protect communities and infrastructure across the catchment.

5.2. Objective Two: To Analyse and Map Inundation Extent for the Identified High-Risk Zones across the Nyabarongo River Catchment in Rwanda

Between 2014 and 2023, flood events in the Nyabarongo catchment increased due to a combination of climate change and human activities. Extreme rainfall, particularly in the March-May seasons of 2018, 2020, and 2022, saw rainfall levels exceed typical annual expectations by over 114%. The rapid urban expansion in Kigali, with its growing hard surfaces, reduced water infiltration, worsening flash floods. Additionally, deforestation and poor farming practices led to soil erosion, which increased sedimentation in rivers, reducing their capacity to manage water.

The study identified significant impacts in high-risk zones, especially in very high-risk areas near the Nyabarongo River and its tributaries. These zones, including croplands, wetlands, and built structures, were heavily affected by flooding due to poor drainage and their proximity to rivers. The inundation maps produced in the study provide valuable insights for flood risk management, helping to guide the development and implementation of effective flood mitigation strategies in these vulnerable regions.

5.3. Objective Three: To Assess the Catchment's Characteristics Mainly Influencing Flood Risk across the Nyabarongo River Catchment in Rwanda

The results revealed that the key factors contributing to flood risk in the Nyabarongo River Catchment include rainfall distribution, proximity to streams, land use, and flow accumulation. Rainfall distribution contributes 22.5% to flood risk, with heavier rainfall in the northern and western regions leading to increased surface runoff and river overflow. Proximity to streams contributes 16.3%, with areas within 100 meters of rivers facing rapid water flow during heavy rainfall. Land use and land cover (LULC), contributing 15.7%, exacerbates flood risk due to urbanization and poor agricultural practices. Flow accumulation and the Stream Power Index (SPI) further enhance flood vulnerability in certain regions.

5.4. Objective Four: To Examine the Relationship between the Catchment's Characteristics and Flood Risk across the Nyabarongo River Catchment in Rwanda

The study demonstrates a strong correlation between catchment characteristics, such as land use, topography, and proximity to water bodies, and flood risk levels. Urbanized areas, agricultural lands, and areas with poor soil conservation practices contribute significantly to increased flood risk. Steep slopes and low-lying areas are particularly vulnerable, with faster runoff and water accumulation observed near streams and rivers. The findings stress the importance of integrated land management practices to mitigate flood risks.

5.5. CONCLUSIONS

The Nyabarongo River catchment study provides crucial insights into flood risk dynamics through comprehensive spatial analysis and environmental assessment. Utilizing the Analytical Hierarchy Process (AHP), the research revealed significant flood risk across the catchment, with risk zones ranging from Very High-Risk (8.6%) to Very Low-Risk (3.5%). Inundation mapping exposed extensive flooding impacts around the Nyabarongo River and its tributaries, affecting croplands, wetlands, and built structures. Key flood risk factors were identified, including rainfall distribution (22.5%), stream proximity (16.3%), and land use (15.7%), demonstrating the complex interactions between environmental parameters and flood susceptibility. The study established a strong correlation between catchment characteristics and flood risk levels. Urbanized areas, agricultural lands, and regions with poor soil conservation practices significantly contribute to flood vulnerability. This analysis underscores the critical importance of ecosystem-based solutions, resilient infrastructure, and community engagement in disaster preparedness.

By providing evidence-based recommendations, the research offers a comprehensive framework for enhancing flood resilience in the Nyabarongo River catchment, Rwanda. The findings emphasize the need for proactive measures and collaborative efforts to mitigate adverse flooding impacts, safeguarding lives, livelihoods, and ecosystems. The methodological approach contributes significantly to understanding flood dynamics, presenting a robust model for assessing environmental vulnerability and supporting more effective natural resource management. Ultimately, the study highlights the importance of integrated catchment management and sophisticated spatial analysis in building community resilience against flooding challenges.

5.6. RECOMMANDATION:

The study recommends a multi-tiered approach to flood risk mitigation in the Nyabarongo River Catchment. At the national level, the government, in collaboration with agencies like the Ministry of Environment and REMA, should prioritize structural measures such as flood barriers, drainage improvements, and floodplain restoration, particularly in high-risk zones. Afforestation, sustainable land management, and tailored solutions for high-rainfall areas (e.g., retention basins) are also emphasized to enhance resilience. Local authorities are urged to adopt community-based strategies, including flood awareness programs, sustainable agriculture (e.g., rainwater harvesting), and strengthened early warning systems, while fostering collaboration with stakeholders to align efforts with community needs.

Local communities play a critical role by maintaining drainage systems, protecting vegetation, and avoiding construction in flood-prone areas. Adopting practices like contour plowing and agroforestry can reduce erosion, while forming flood response teams and partnering with authorities on emergency plans will improve preparedness. The study further calls for research institutions to investigate long-term impacts of land use and climate change, innovate flood management strategies, and address gaps in current data. Together, these recommendations aim to build systemic and community-level resilience against flooding in the region.

REFERENCES

1. Africa News. (2023, May 3). *Over 100 die in floods in Rwanda's Western and Northern Provinces*. Africa news. https://www.africanews.com/2023/05/03/over-100-die-in-floods-in-rwandas-western-and-northern-provinces/
2. Banjara, M., Bhusal, A., Ghimire, A. B., & Kalra, A. (2024). Impact of Land Use and Land Cover Change on Hydrological Processes in Urban Watersheds: Analysis and Forecasting for Flood Risk Management. *Geosciences*, *14*(2), Article 2. https://doi.org/10.3390/geosciences14020040
3. Bizoza, A. R., & Rutikanga, C. (2018). *Assessment of land use and land cover changes and their implications on floods in Rwanda: A case of Nyabarongo Upper Catchment.* Rwanda Journal of Engineering, Science, Technology and Environment, 1(1), 34–47.
4. Bizimana, J. P., & Schilling, J. (2021). Land use and land cover change and its effects on flood risk in the Nyabarongo River Catchment, Rwanda. *Environmental Challenges*, 5, 100243. https://doi.org/10.1016/j.envc.2021.100243
5. Barrow, J. M., Brannan, G. D., & Khandhar, P. B. (2023). Research Ethics. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK459281/
6. DCIF. (2022). *Water / Rwanda | Interactive Country Fiches*. https://dicf.unepgrid.ch/rwanda/water
7. El-Bagoury, H., & Gad, A. (2024). Integrated Hydrological Modeling for Watershed Analysis, Flood Prediction, and Mitigation Using Meteorological and Morphometric Data, SCS-CN, HEC-HMS/RAS, and QGIS. *Water*, *16*(2), Article 2. https://doi.org/10.3390/w16020356
8. Fineman, M. A. (2019). *Vulnerability and Social Justice* (SSRN Scholarly Paper No. 3352825). https://doi.org/10.2139/ssrn.3352825
9. Gasirabo, A., Xi, C., Kurban, A., Liu, T., Baligira, H. R., Umuhoza, J., Umugwaneza, A., & Dufatanye Edovia, U. (2023). SWAT model calibration for hydrological modeling using concurrent methods, a case of the Nile Nyabarongo River basin in Rwanda. *Frontiers in Water*, *5*. https://doi.org/10.3389/frwa.2023.1268593
10. Gasirabo, A. (2023). SWAT model calibration for hydrological modeling using concurrent methods, a case of the Nile Nyabarongo River basin in Rwanda. *Frontiers in Water*, *5*. doi: https://doi.org/10.3389/frwa.2023.1268593
11. Karamage, F., Zhang, C., Kayiranga, A., Shao, H., Fang, X., Ndayisaba, F., Nahayo, L., Mupenzi, C., & Tian, G. (2016a). USLE-Based Assessment of Soil Erosion by Water in the Nyabarongo River Catchment, Rwanda. *International Journal of Environmental Research and Public Health*, *13*(8), Article 8. https://doi.org/10.3390/ijerph13080835
12. Karamage, F., Zhang, C., Kayiranga, A., Shao, H., Fang, X., Ndayisaba, F., Nahayo, L., Mupenzi, C., & Tian, G. (2016b). USLE-Based Assessment of Soil Erosion by Water in the Nyabarongo River Catchment, Rwanda. *International Journal of Environmental Research and Public Health*, *13*(8), Article 8. https://doi.org/10.3390/ijerph13080835
13. Kawera, J. (2024). *More than 130 lost lives and properties due to floods and landslide disasters in Rwanda – Rwanda Climate Change and Development Network*. https://rccdnetwork.org/?p=1259
14. Kelly, M., & Kuleshov, Y. (2022). Flood Hazard Assessment and Mapping: A Case Study from Australia's Hawkesbury-Nepean Catchment. *Sensors (Basel, Switzerland)*, *22*(16), 6251. https://doi.org/10.3390/s22166251
15. Koralay, N., & Kara, Ö. (2024). Assessment of flood risk in Söğütlü stream watershed of Trabzon province in Turkey using geographic information systems and analytic hierarchy process approach. *Natural Hazards*, *120*(11), 9977–10000. https://doi.org/10.1007/s11069-024-06594-1
16. 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* [Master Thesis]. http://repository.pauwes-cop.net/handle/1/141
17. Liu, S. (2024). Impact of Exchange Rate Fluctuation on Import and Export Enterprises in China and Japan and Countermeasures. *Highlights in Business, Economics and Management*, *24*, 322–330. https://doi.org/10.54097/4mmr4q90
18. Lu, Y., & Shutian , Z. (2024). An integrated Bayesian networks and Geographic information system (BNs-GIS) approach for flood disaster risk assessment: A case study of Yinchuan, China. *Ecological Indicators*. doi:https://doi.org/10.1016/j.ecolind.2024.112322
19. Lu, Y., Zhai, G., & Zhou, S. (2024). An integrated Bayesian networks and Geographic information system (BNs-GIS) approach for flood disaster risk assessment: A case study of Yinchuan, China. *Ecological Indicators*, *166*, 112322. https://doi.org/10.1016/j.ecolind.2024.112322
20. Manikuze, P. (2021). Vulnerability of Nyabarongo River Water Abstraction to Climate Change in Rwanda. *IAR Consortium*. https://www.academia.edu/59905163/Vulnerability_of_Nyabarongo_River_Water_Abstraction_to_Climate_Change_in_Rwanda
21. McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, *19*(2). https://www.jstor.org/stable/2626958

22. Menton, M., Larrea, C., Latorre, S., Martinez-Alier, J., Peck, M., Temper, L., & Walter, M. (2020). Environmental justice and the SDGs: From synergies to gaps and contradictions. *Sustainability Science*, *15*(6), 1621–1636. https://doi.org/10.1007/s11625-020-00789-8
23. Mind'je, R., Li, L., Kayumba, P. M., Mindje, M., Ali, S., & Umugwaneza, A. (2021a). Integrated Geospatial Analysis and Hydrological Modeling for Peak Flow and Volume Simulation in Rwanda. *Water*, *13*(20), Article 20. https://doi.org/10.3390/w13202926
24. Mind'je, R., Li, L., Kayumba, P. M., Mindje, M., Ali, S., & Umugwaneza, A. (2021b). Integrated Geospatial Analysis and Hydrological Modeling for Peak Flow and Volume Simulation in Rwanda. *Water*, *13*(20), Article 20. https://doi.org/10.3390/w13202926
25. Nhapi, I. (2011). Assessment of Water Pollution Levels in the Nyabugogo Catchment, Rwanda. *The Open Environmental Engineering, 4*(1). doi:10.2174/1874829501104010040
26. Niyonzima, S., & Gasirabo, A. (2021). Slope characteristics and soil erosion risk in the Nyabarongo upper catchment. International Soil and Water Conservation Research, 9(3), 340–350. https://doi.org/10.1016/j.iswcr.2021.03.005
27. Nambajimana, J. de D., He, X., Zhou, J., Justine, M. F., Li, J., Khurram, D., Mind'je, R., &
28. Nsabimana, G. (2020). Land Use Change Impacts on Water Erosion in Rwanda. *Sustainability*, *12*(1), Article 1. https://doi.org/10.3390/su12010050
29. Nsengiyumva, J. B., Rulinda, C. M., & Wali, U. G. (2018). Topographic analysis and hydrological characterization of the Nyabarongo River Basin. *Journal of African Earth Sciences*, 145, 133–143. https://doi.org/10.1016/j.jafrearsci.2018.04.021
30. Niyonzima, S., & Gasirabo, A. (2021). Slope characteristics and soil erosion risk in the Nyabarongo upper catchment. *International Soil and Water Conservation Research*, 9(3), 340–350. https://doi.org/10.1016/j.iswcr.2021.03.005
31. Nguyen, T. T., Nakatsugawa, M., Yamada, T. J., & Hoshino, T. (2021). Flood Inundation Assessment in the Low-Lying River Basin Considering Extreme Rainfall Impacts and Topographic Vulnerability. *Water*, *13*(7), Article 7. https://doi.org/10.3390/w13070896
32. Nkurunziza, M. (2022, November 29). *Nyabarongo floods continue to put road transport at risk*. The New Times. https://www.newtimes.co.rw/article/3122/news/environment/nyabarongo-floods-continue-to-put-road-transport-at-risk
33. Nsengimana, V., Weihler, S., & Kaplin, B. A. (2017). Perceptions of Local People on the Use of Nyabarongo River Wetland and Its Conservation in Rwanda. *Society & Natural Resources*, *30*(1), 3–15. https://doi.org/10.1080/08941920.2016.1209605
34. Nyam, Y., & Modiba, N. (2024). Analysis of the perceptions of flood and effect of adoption of adaptation strategies on income of informal settlements of Mamelodi in South Africa. *Climate Services, 34*. doi:https://doi.org/10.1016/j.cliser.2024.100468
35. OCHA. (2024a, July 4). *Rwanda: Floods - Apr 2024 | ReliefWeb*. https://reliefweb.int/disaster/fl-2024-000064-rwa
36. OCHA. (2024b, October 3). *Rwanda: Floods - Apr 2024 | ReliefWeb*. https://reliefweb.int/disaster/fl-2024-000064-rwa
37. REMA (Rwanda Environment Management Authority). (2019). *Rwanda Environment and Climate Change Policy*. Kigali: Government of Rwanda.
38. Relief web. (2024, September 3). *Rwanda: Floods and Landslides - May 2023 | ReliefWeb*. https://reliefweb.int/disaster/fl-2023-000064-rwa
39. Sarchani, S., Seiradakis, K., Coulibaly, P., & Tsanis, I. (2020). Flood Inundation Mapping in an Ungauged Basin. *Water*, *12*(6), Article 6. https://doi.org/10.3390/w12061532
40. Statista. (2024). *Africa: Flood risk 2022*. Statista. https://www.statista.com/statistics/1313372/physical-exposure-to-floods-by-country-africa/
41. Stein, L., Clark, M. P., Knoben, W. J. M., Pianosi, F., & Woods, R. A. (2021). How Do Climate and Catchment Attributes Influence Flood Generating Processes? A Large-Sample Study for 671 Catchments Across the Contiguous USA. *Water Resources Research*, *57*(4), e2020WR028300. https://doi.org/10.1029/2020WR028
42. Sugianto, S., Deli, A., Miswar, E., Rusdi, M., & Irham, M. (2022b). The Effect of Land Use and Land Cover Changes on Flood Occurrence in Teunom Watershed, Aceh Jaya. *Land*, *11*(8), Article 8. https://doi.org/10.3390/land1108127
43. Yari, A., Ostadtaghizadeh, A., Ardalan, A., Zarezadeh, Y., Rahimiforoushani, A., & Bidarpoor, F. (2020). Risk factors of death from flood: Findings of a systematic review. Journal of Environmental Health Science and Engineering, 18(2), 1643–1653. https://doi.org/10.1007/s40201-020-00511-x