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Assessment of flood susceptibility utilizing remote sensing and geographic information systems: A case study of Mpazi sub-catchment in the city of Kigali

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Abstract

The Mpazi sub-catchment has been facing recurring floods, which pose significant threats to the community and environment. However, GIS technology has proven to be a valuable tool in assessing flood risks and vulnerability in the region. By analyzing spatial data such as land use, elevation, and rainfall patterns, detailed flood maps can be generated to simulate flood scenarios and develop effective management plans. The study conducted in this region revealed that there is a high susceptibility to flood hazards, particularly during the rainy season. The study identified the most vulnerable areas in the region and categorized them as follows: very high risk (39.74%), high risk (13.02%), moderate risk (30.22%), low risk (5.12%), and very low risk (11.9%). It is important to note that floods not only impact the environment but also infrastructure, such as residential and commercial buildings. The insights provided by this study are invaluable for stakeholders in developing effective flood management strategies to mitigate. Hence, all concerned government departments and citizens should collaborate actively to alleviate the ongoing rise in flooding and its impact. Adherence to land use and zoning regulations is crucial in this regard to address the issue effectively.

1. Introduction

Globally, many people are exposed to high vulnerability to natural disasters and other environmental changes because of climate change (Wali et al., 2013). This is because the climate has changed and is continuously changing on a global basis, and as a result, there are natural increases in the frequency and severity of natural disasters (Estrada et al., 2023). They are the most common natural disasters that occur when the river channel receives much more water than the usual amount it can receive (Andrews et al., 2017). The result of excessive rainfall is that the rivers rise, and a flood develops because the river cannot handle the extra water, causing flooding everywhere along the river's path. The result of excessive rainfall is that the rivers rise, and a flood develops because the river cannot handle the extra water, causing flooding everywhere along the river's path (Wali et al., 2013). This implies that all elements at risk such as population are highly affected by floods i.e., the more vulnerable a population is, the more likely they are to suffer the consequences of a flood event (Cutter et al., 2008). The areas with high levels of poverty and inadequate infrastructure are more vulnerable to floods and experience higher impacts. For example, low-income areas in urban environments are often at high risk of flooding and have higher levels of vulnerability due to factors such as poor drainage systems and lack of access to information (Bubeck et al., 2012).

Similarly, the vulnerability of critical infrastructure such as hospitals and schools is a key factor in determining the impact of floods on communities, and therefore, the more critical infrastructure that is damaged or destroyed, the more difficult it is to provide emergency services and restore regularity (Pant et al., 2018). Moreover, vulnerability and exposure to flood risk are important factors in determining the impact of floods

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on agricultural production; this is to say that areas with higher vulnerability and exposure to flood risk experience more significant reductions in agricultural productivity following a flood event (Wang et al., 2013).

Many African countries are particularly vulnerable to flooding, which is made worse for several reasons, including climate change, urbanization, deforestation, and inadequate infrastructure (Pörtner et al., 2019). Africa is the continent most affected by floods, with an average of 3.4 million people affected annually between 2000 and 2018, the number of flood events in Africa has also been increasing, with a 50% increase in the frequency of floods between 1995 and 2015 (Loke et al., 2021). Floods in Africa often result in significant economic and social impacts, with loss of life, damage to infrastructure and property, and disruption of livelihoods. In many cases, vulnerable communities are disproportionately affected, with women and children being particularly at risk (Pörtner et al., 2019). By the end of the 20th century, the research examined the impact of climate change on flood hazards in West Africa and found that flood frequency and magnitude are projected to increase significantly, with the potential to affect millions of people, and the study also emphasized the need for proactive flood risk management strategies to mitigate the potential impacts of climate change on vulnerable communities in the region (Alfieri et al., 2016).

In East Africa, flood vulnerability is a significant issue affecting millions of people every year. The region is prone to floods due to heavy rainfall, poor drainage systems, deforestation, and climate change. Flood events in East Africa have had devastating impacts, including the destruction of homes and infrastructure, contamination of water sources, and an increased risk of illness (Birmah et al., 2021). In 2015, heavy rains caused severe flooding in several East African countries, including Ethiopia, Kenya, and Somalia; as a result, over 100,000 people were affected, and at least 40 people died because of the floods (Gamoyo et al., 2015); and in 2017, over 300,000 people were displaced, and at least 100 people died because of the floods (UNICEF, 2018). While flood hazard is natural, human influence in the variation and modification of urban space worsens the problem where the terrible consequences are dependent on the degree of human activities and occupancy in vulnerable areas (Cirella et al., 2018; Mashi et al., 2020; Wahab & Falola, 2022).

Nyabugogo watershed, particularly Mpazi sub-catchment the focus of this research has experienced flooding in several incidents. This is mostly because Mpazi sub-catchment is located at a low altitude relative to its surroundings and the peculiarities of the Kigali city drainage system convergence zone, which has frequently experienced flooding (Gerard, 2014). When flooding happens in this region, the damaged materials and the soil eroded from the upper stream flow with the water through the river channel, and as a result, they are deposited downstream, ultimately closing the drainage channels (Manyifika, 2015). All the materials and eroded soil cause the channel to be blocked, and the water cannot flow as it should, which causes the surrounding area to flood. Mpazi channel, which receives upstream rainwater, is one of the main causes of flooding in this area. Since the channel is blocked by debris, eroded soil, and damaged materials, the water cannot, therefore, flow as it should, which suddenly causes the surrounding areas to flood. The Nyabugogo River, especially the Mpazi channel, which receives rainwater from upstream, is one of the main causes of flooding in this area (Gerard, 2014). All the rainwater from Gitega, Kimisagara, Muhima, and Nyabugogo areas falls into Nyabugogo River during the rainy season, and this leads to frequent floods in this area, which are known as flash floods. Flash floods are sudden, rapid floods that can occur within a few minutes or hours of heavy rainfall or other causes of rapid water accumulation; these floods are highly dangerous and destructive, as they often catch people off guard and can quickly overwhelm infrastructure and buildings. Flash floods typically occur in low-lying areas or in as with poor drainage, and they can be triggered by intense rainfall, dam, or levee failures, or other natural or man-made factors that cause a sudden influx of water (Alarifi et al., 2022; Mind'je et al., 2019). About 8 km^2 of the urban area is drained to the Nyabugogo River. Eventually, it is characterized by flash floods, which suddenly put people at risk and destroy socio-economic infrastructures (Manyifika, 2015; Habonimana et al., 2015).

Geographical Information system (GIS) is a critical tool in flood management (Peker et al., 2024). Floods are major natural disasters that can cause significant damage to communities, infrastructure, and the environment (Njogu, 2021). The increasing frequency and severity of floods, attributed to climate change, have led to a growing need for effective flood management strategies (Dub et al., 2022). Geographical Information System has emerged as a powerful tool to support flood management, providing valuable information and analysis to decision-makers to support the planning and response to floods (Bilașco et al., 2022). GIS is used for various purposes in flood management, starting with flood risk assessment, where GIS analyzes topographical, hydrological, and meteorological data to identify high-risk areas and develop risk reduction strategies (Hadipour et al., 2020).

Subsequently, GIS is used to create flood hazard maps, which are generated by analyzing elevation, slope, land use, soil type, and rainfall data, among others, providing useful information for planning and responding to floods (Poussin et al., 2015). Real-time flood monitoring is another application of GIS in flood management. It involves using remote sensing, and citizen-generated data to identify areas that require immediate attention and to inform emergency response efforts (Khedo, 2013). Furthermore, GIS is used to develop early warning systems that provide timely and accurate information about potential floods, issuing alerts to communities and decision-makers, and is used to develop flood risk reduction strategies such as the construction of flood protection infrastructure, land use planning, and public education campaigns, aiming to minimize the impact of floods on communities and reduce the risk of flooding (Cai et al., 2021).

This study intends to combine geospatial data to identify flood vulnerability areas located in flood-prone areas. In past research that attempted to examine flood vulnerability in Mpazi sub-catchment, the use of GIS technology to display flood-prone areas was insufficient. This knowledge gap motivates this study to use GIS-based analysis to map flood-prone areas within the Mpazi sub-catchment sufficiently. The insufficient use of GIS-based vulnerability assessments in flood-prone areas of the Mpazi sub-catchment presents a knowledge gap that this study aims to address. This study intends to combine geospatial data to identify flood vulnerability areas located in flood-prone areas by using the GIS-AHP method, to provide valuable information to contribute to the development of effective flood risk management strategies in the region and eventually help policymakers to take some coping strategies and adaptive measures to reduce flood risks. This literature synthesis presents key findings, and contributions from different studies, highlighting the complex interplay between vulnerability, climate dynamics, and the role of GIS tools in effective flood risk assessment and management (Table 1).

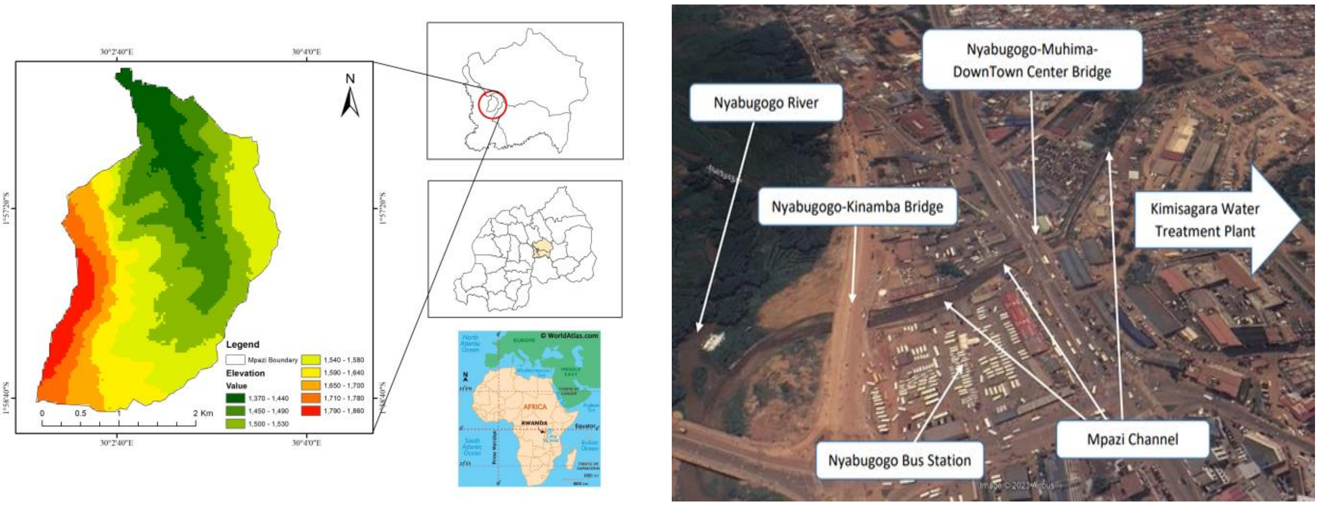
Table 1. Research literature summary

Reference	Key findings	Contribution to research
(Wali et al., 2013)	Climate change contributes to increased vulnerability to natural disasters globally	Linking between climate change and heightened vulnerability to natural disasters.
(Estrada et al., 2023)	Ongoing global climate change leads to a rise in the frequency and severity of natural disasters.	Emphasizes the continuous impact of climate change on the frequency and severity of natural disasters.
(Peker et al., 2024)	GIS is a critical tool in flood management, offering support in flood risk assessment, hazard mapping, real-time monitoring, and early warning systems.	Recognizes GIS as a powerful tool in various aspects of flood management, including assessment and monitoring.
(Manyifika, 2015)	Flooding in Mpazi sub-catchment leads to debris and eroded soil blockages in the river channel, causing flash floods and extensive damage in downstream areas.	Describes the consequences of flooding in Mpazi sub-catchment, specifically the occurrence of flash floods due to channel blockages.

2. Materials and method

2.1. Study area

The study is concentrated on the Mpazi sub-catchment, which is wholly enclosed inside the Nyarugenge district (Figure 1, 2). One of the Nyabugogo catchment sub-catchments, the Mpazi sub-catchment, lies between 10 56'15" and 10 58'45"S and between 300 02'00'E and 300 03'45"E. This sub-sub-catchment is found in Nyarugenge District in western Kigali City and covers an area of 888.90 ha.



(a) (b)

Figure 1. (a) Study area, (b) Mpazi sub-catchment downstream (Google Earth Pro, 2023)

In Mpazi sub-catchment, the average annual temperature ranges from 16°C to 20°C, its climate is defined by two rainy seasons that typically last from February to May and from mid-September to mid-December with approximately 1,250 to 1,300 mm of rain falling on average each year (Balana et al., 2020). As compared to the rest of the watershed, the Mpazi section is estimated to have the highest peak runoff discharge (flow) at 107.5 m^3/s for 25 years (Habonimana et al., 2015). The geological structure is composed of meta-sedimentary and granite rocks such as schist, sandstones, and siltstones (Balana et al., 2020). Hillside surfaces are covered in lateritic soils that are rich in iron and aluminum, while lowlands and wetlands have alluvial and organic soils (Bizimana, & Ndahigwa, 2020).

2.2. Data processing methods

Choosing the right factors or criteria is crucial for a detailed flood vulnerability assessment. This is particularly important in identifying and mapping natural hazards such as landslides, floods, and cyclones, which rely on various factors for their occurrence. To create an accurate flood vulnerability map for a particular catchment area, it is imperative to carefully select the most appropriate factors (Rimba et al., 2017; Roy & Blaschke, 2015; Shivaprasad et al., 2018).

However, this can be challenging, as selecting parameters that consistently produce accurate susceptibility maps requires careful consideration and attention to detail. The selection of criteria and alternatives for flood vulnerability assessment in the Mpazi sub-catchment was based on a detailed literature review, data availability, and their relevance and impact on flood vulnerability. The analysis of vulnerability in this study focuses on the physical and natural factors that control and influence it. These factors have been identified and selected as criteria for the analysis. The study has identified five vulnerability criteria from different sources. The land use and cover map of the study area was delivered from data produced by Rwanda GeoPortal 2020. Slope data and elevation map were generated from Digital Elevation Model (DEM) data obtained from the United States Geological Survey portal (USGS). The precipitation map of the study area was delivered from the interpolation of data from Meteo Rwanda. To process and prepare the numerous spatial criterion layers, ArcGIS software (version 10.8) was used. The Analytical Hierarchy Process (AHP) technique is a GIS-based decision-making method and was delivered to weigh the criteria based on the information gathered during the field survey and literature review. This enabled the development of a more accurate and comprehensive assessment of flood vulnerability in the Mpazi sub-catchment.

TIFF Web-based Data derived from the Esri Land Cover-Living Atlas for Land Use and Land Cover (LuLc) is presented at a spatial resolution of 10 meters. This means that each pixel in the imagery represents an area on the Earth's surface with dimensions of 10 meters by 10 meters. STRM-DEM (Shuttle Radar Topography Mission - Digital Elevation Model) obtained from the USGS Earth Explorer has a spatial resolution of 10 meters. This indicates that each pixel in the digital elevation model corresponds to a 10-meter-by-10-meter area on the ground (Table 2).

Table 2. Data types and sources

Data Type & Resolution	Source	Period	Mapping Output
TIFF Web-based Data (10m Resolution)	Esri Land Cover-Living Atlas	2019-2021	LuLc
STRM-DEM (10m Resolution)	USGS Earth Explorer	2023	Elevation and Slope
Precipitation	Meteo Rwanda	2021	Precipitation
River buffers	Google Earth Pro	2023	Proximity analysis

2.3. Identification of criteria

Land use, particularly the built-up areas, is a critical factor that influences flooding in the study area. When natural surfaces such as vegetation and soils are replaced by impervious surfaces such as concrete and asphalt, the surface runoff increases, leading to more flooding. In the Mpazi sub-catchment, built-up areas also reduce the amount of infiltration, causing more water to flow into the streams and rivers, increasing the volume of water, which causes flooding, especially in low-lying sub-catchment areas. Generally, low-lying areas with gentle slopes are more susceptible to flooding than those with higher elevations and steeper slopes (Hu et al., 2017) (Figure 2).

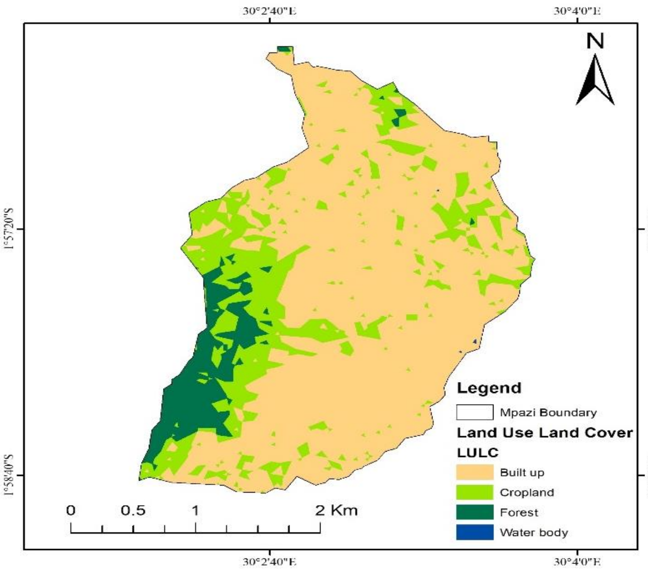


Figure 2. LuLc map

Another important flood risk factor is distance from the river channel (Figure 3). The lower the distance from the river, the higher the flood risk level. Precipitation is crucial to flood risk. When the precipitation increases, the flood risk also is higher (Rimba et al., 2017).

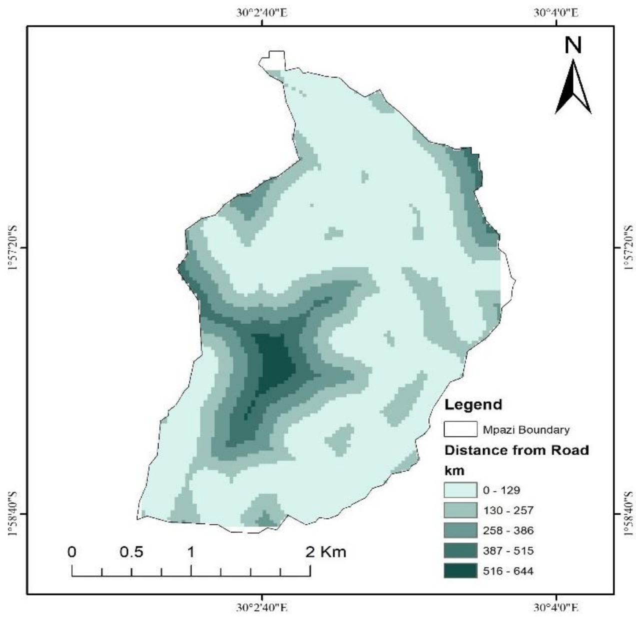


Figure 3. Flood criteria map distance from river

The Topographical Wetnex Index is another important factor that contributes to flood vulnerability. The topographic wetness index (TWI) is crucial in flood vulnerability assessment. TWI measures the land's capability to retain water and indicates areas of potential water accumulation during flooding events. Considering the TWI in flood vulnerability assessments, it is possible to identify low-lying areas with poor drainage and higher flood susceptibility. Areas with high TWI values are likely to have higher water saturation, resulting in increased vulnerability to flooding. Additionally, TWI can help prioritize flood mitigation efforts and inform land use planning by identifying areas where development should be avoided or proper water management measures should be implemented. The study area with levels >2-7 tends to be wet and more vulnerable to risk compared to areas with low wetness (Figure 4).

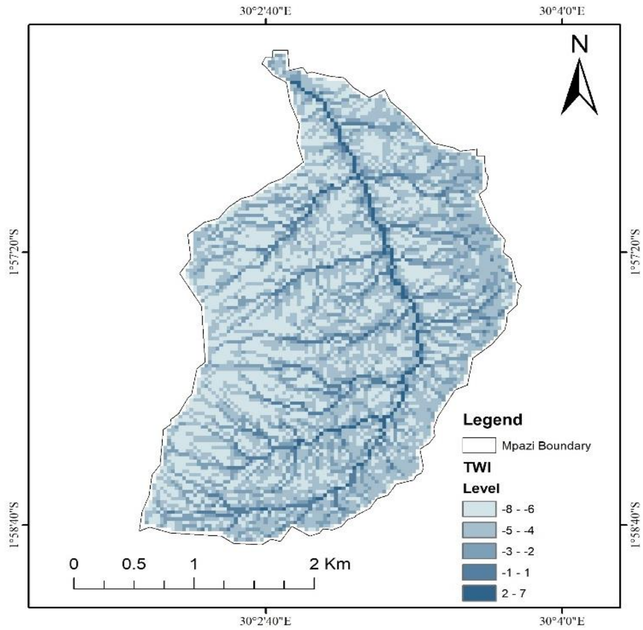


Figure 4. Topographical Wetnex Index map

The influence of slope and elevation in flood vulnerability assessment is significant. Slope affects the speed and direction of water flow during floods, impacting the intensity and spread of flooding. Areas with steeper slopes tend to channel water more rapidly, increasing flood hazards. Elevation is crucial in flood vulnerability, as low-lying areas are more prone to inundation (Figure 5).

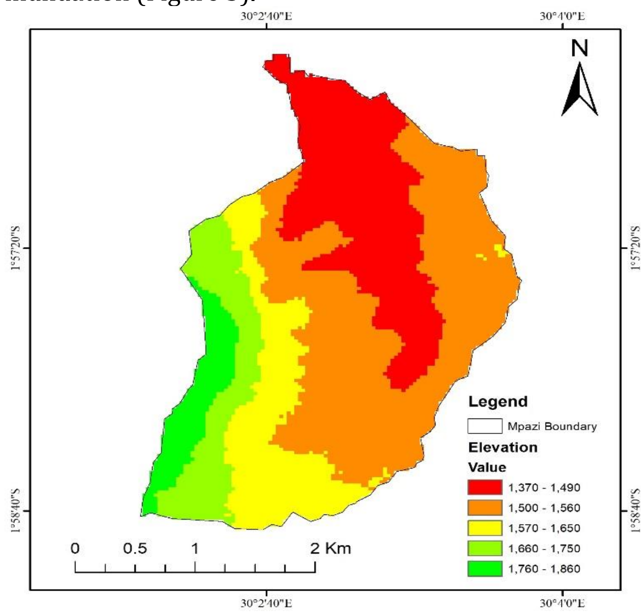


Figure 5. Elevation map

Higher elevations offer natural protection from flooding. Generally, low-lying areas with gentle slopes are more susceptible to flooding than those with higher elevations and steeper slopes (Hu et al., 2017) (Figure 6).

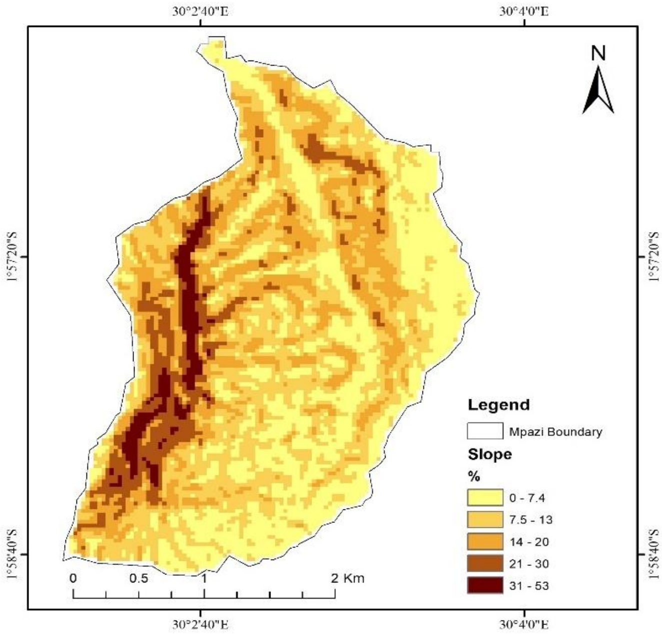


Figure 6. Slope map

Precipitation intensity is a crucial criterion that has a significant impact on the level of flood vulnerability (Rimba et al., 2017). Regions that experience higher levels of precipitation intensity are at a greater risk of flooding compared to areas with lower levels of precipitation intensity (Figure 7).

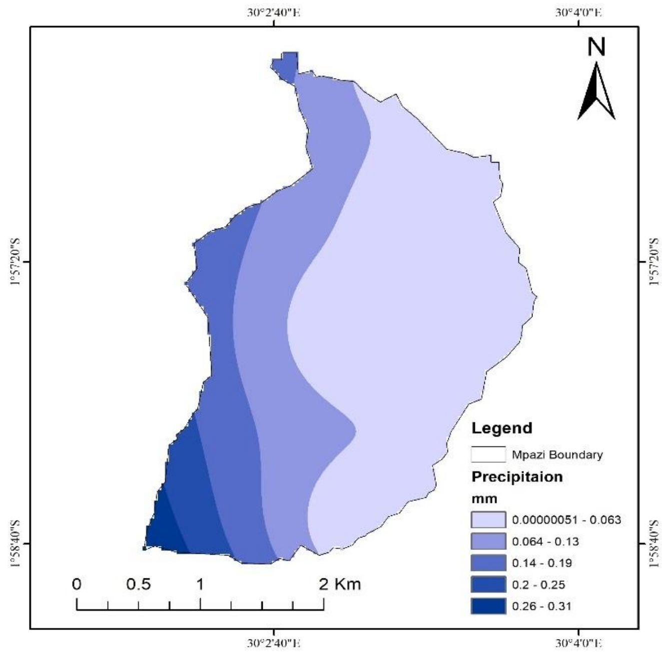


Figure 7. Precipitation map

Table 3. Scale of relative importance (adapted from Saaty (Saaty, 2002))

Relative Importance	Definition	Description
1	Equal importance	Two factors equally influence the objective
3	Moderate importance	Experience and judgment slightly favour one factor over another
5	Strong importance	Experience and judgment strongly favour one factor over another
7	Very strong importance	One decision factor is strongly favoured over another, and its supremacy is established in practice
9	Extreme importance	The evidence favouring one decision factor over another is of the highest possible orders of validity
2, 4, 6 and 8	Intermediate values between adjacent judgement	When compromise is required

The study has recognized the significance of these factors and aims to integrate them into the assessment of flood vulnerability by creating spatial thematic layers. The results of our GIS analysis reveal that areas with low elevations and steep slopes are highly vulnerable to flooding, which is consistent with previous studies. In this research, the Analytic Hierarchy Process (AHP) methodology was used to assign weights to the criteria for flood vulnerability (Table 3-5). The construction of pairwise comparison matrices was undertaken to quantify the criteria weights, drawing upon qualitative assessments provided by five experts and a user. The criteria were assigned weights based on the scale of relative importance proposed by Saaty (Saaty, 2002).

Table 4. Comparison matrix for flood risk criteria

Criteria	LuLc	Precipitation	Slope	TWI	Elevation	Distance from River
LULC	1	3	3	3	3	3
Precipitation	1/3	1	1/3	1/3	1/3	1/3
Slope	1/3	3	1	1/3	1/3	1/3
TWI	1/3	3	3	1	1/3	1
Elevation	1/3	3	3	3	1	3
Distance from River	1/5	1/3	1/3	1/3	1/3	1/3

Table 5. Flood risk classes and weights

Criteria	Unit	Very High	High	Moderate	Low	Very Low	Weights
LuLc	Level	Waterbody	Agricultural land	Built-Up	Bare land	Vegetation	0.178
Precipitation	mm	0.26 – 0.31	0.2 – 0.25	0.14 – 0.19	0.1-0.13	<0.1	0.262
Slope	%	0 – 7.2	7.3 – 13	14 – 20	21 – 30	31 - 53	0.145
TWI	Level	2 - 7	-1 – 1	-3 - -2	-5 - -4	-8 - -6	0.090
Elevation	m	>1370 – 1490	1500 – 1560	1570-1650	1660 - 1750	1760 - 1860	0.100
Distance from river	m	<129	>130 – 257	>258 – 386	>387 – 515	>516 - 644	0.225

3. Results

Choosing the right factors or criteria is crucial in conducting a detailed flood vulnerability assessment. This is particularly important in identifying and mapping natural hazards such as landslides, floods, and cyclones, which rely on various factors for their occurrence (Roy & Blaschke, 2015). By comparing the criteria weighted with the highest influence on flooding risk in the study area were calculated, precipitation (0.262); distance from the river (0.225); LuLc (0.17); slope (0.145); elevation (0.1); TWI (0.09). The flood vulnerability map identifies the most vulnerable areas to flooding in the study area, very high risk 39.74% (353.34 ha), high risk 13.02% (115.73 ha), moderate risk 30.22% (268.62 ha), low risk 5.12% (45.51 ha), very low risk 11.9% (105.77 ha) (Table 6).

Table 6. Flood risk areas in Mpazi sub-catchment

Flood Risk Classes	Area (km^2)	Rate (%)
Very Low	105.77	11.90
Low	45.51	5.12
Moderate	268.62	30.22
High	115.73	13.02
Very High	353.34	39.74

According to the field survey, infrastructures such as residential houses, trading centers, roads and bridges are frequently affected by flooding (Figure 8).

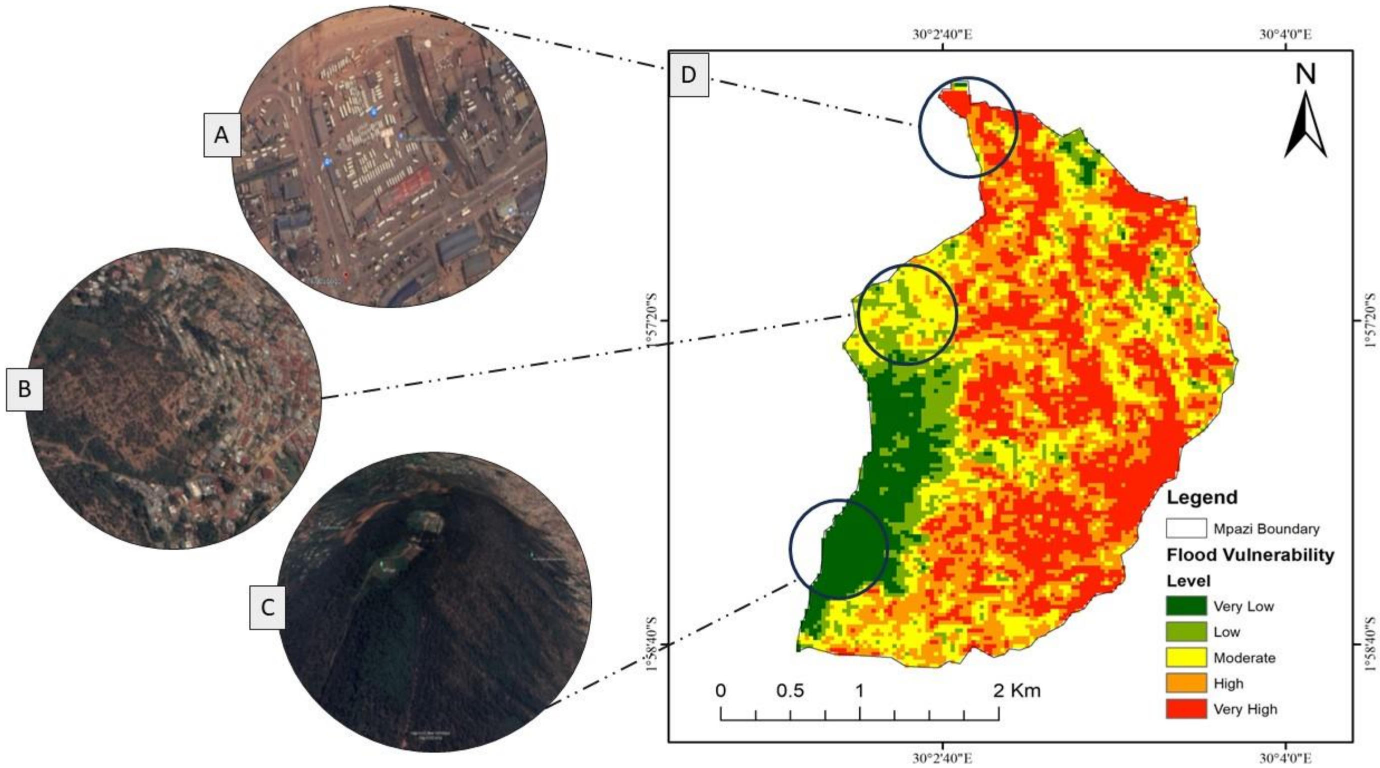


Figure 8. Flood risk map of Mpazi sub-catchment

The flood vulnerability map produced in this study for the Mpazi sub-catchment indicates that the area is highly susceptible to flooding. The map reveals that the highest flood vulnerability is concentrated in the eastern and northeastern parts of the sub-catchment, which are predominantly urban areas. These areas have high population densities, the land is mostly covered by impervious surfaces such as buildings, roads, and pavements. The flood vulnerability map produced in this study for the Mpazi sub-catchment indicates that the area is highly susceptible to flooding. The map reveals that the highest flood vulnerability is concentrated in the eastern and northeastern parts of the sub-catchment, which are predominantly urban areas. These areas have high population densities, and the land is mostly covered by impervious surfaces such as buildings, roads, and pavements. The study also found that the areas with the highest flood vulnerability are near the Nyabugogo River, which is prone to flooding during heavy rainfall. Additionally, the map shows that areas with steep slopes and poor soil drainage are also highly vulnerable to flooding. On the other hand, the western and southwestern parts of the sub-catchment have a lower flood vulnerability, as they are characterized by low population densities, agricultural land use, and gentle slopes. The results of this study highlight the need for effective flood management strategies in the highly vulnerable areas of the sub-catchment, particularly in urban areas with high population densities.

The areas which are more vulnerable to flooding are affected by the floods and loss of lives. Floods result in loss of life due to drowning or other flood-related injuries. People in highly vulnerable areas may be more likely to be caught off-guard by flooding, increasing the risk of fatalities (Habonimana et al., 2015). Damage to infrastructure; roads, bridges, and other infrastructure in highly vulnerable areas (Figure 8) making it difficult for emergency responders to access affected areas. This can also disrupt supply chains and commerce, leading to economic losses. In addition, in more vulnerable to flooding areas, floods lead to loss of property where they destroy or damage homes, businesses, and other property, leaving people without shelter or possessions. This can be especially devastating for those in highly vulnerable areas who may not have insurance or other resources to recover from such losses. Loss of property, floods can destroy or damage homes, businesses, and other property, leaving people without shelter or possessions. This can be especially devastating for those in highly vulnerable areas who may not have insurance or other resources to recover from such losses. Therefore, the effects of floods in highly vulnerable areas of Mpazi sub-catchment can be devastating and long-lasting. It is important to take steps to mitigate the risks of flooding, including improved infrastructure, early warning systems, and disaster preparedness planning.

4. Discussion

The areas which are more vulnerable to flooding are those very close to the active river channel. Also, the lowlands (low elevated areas) areas are at high risk because of overflow of water (Figure 8a). The reverse is true, which means the areas with high elevation are likely to have vegetation cover and this place is not more vulnerable to flooding (Figure 8c). The frequency, intensity, and impact of flooding are growing and causing more negative impacts on humans, the economy, and the environment (Mind'je et al., 2019).

A combination of engineering measures and nature-based solutions is essential to reduce flood risk effectively. Constructing retaining walls and planting vegetation cover are vital components of flood risk reduction, as they help to manage water flow and prevent erosion. However, in addition to these conventional approaches, developing nature-based solutions like Natural Water Retention Measures (NWRM) and Natural Flood Management (NFM) is becoming increasingly crucial. NWRM enhances natural features like wetlands and forests to absorb excess water. Natural water retention measures are "a multifunctional form of green infrastructure that can play an important role in catchment-scale flood risk management natural means and processes" (Taramelli et al., 2019). They include afforestation of upstream catchments; targeted planting for catching precipitation; maintenance of riparian buffers; urban forests; Land-use conversion for water quality improvements; green roofs and walls; rainwater harvesting; permeable paving; swales; soak ways; infiltration trenches; rain gardens; growth of urban green spaces; detention basins; permeable paving; retention ponds; urban channel restoration; etc. (Seddon et al., 2020).

NWRM can be performed for flood risk reduction either within Mpazi sub-catchment, for instance, the green roof is designed to intercept rainfall since it is slowed as it passes through the vegetation (Zeleňáková et al., 2017) and it can be implemented into very high-risk areas especially the low-lying slope of the region. The drainage layer stores some of the rainwater, which is then absorbed by the vegetation and the remaining water is then released from the roof as usual. In comparison to a normal roof, the flow rates from a green roof are lower and attenuated, and the total volumes discharged from the roof are lower (Figure 9a). Therefore, green roofs catch rainwater at their source and serve as the foundation of sustainable flood control management; permeable paving is made to allow rainwater to permeate through the surface into the soils beneath it to facilitate more infiltration. It can most be frequently employed on road networks and parking areas (Mohammadreza Hassani et al., 2017). Permeable paving can be practiced in Nyabugogo car park. The main purpose of channels is to capture runoff, permit sediment deposition, and transport the runoff to features farther downstream in the sustainable drainage network (Collentine & Futter, 2018) and it can be helpful when implemented around Nyabugogo car park where during heavy rainfall, runoff water is captured through drainage channels to reduce water from floating Stone-filled infiltration trenches (Figure 9d) are made up with sands and gravels, can assist recharge groundwater, maintain river base flow, and minimize runoff volumes and rates (Mashi et al., 2020), and those infiltration trenches are typically well suited for areas that generate large amounts of sediment especially low-lying areas near Nyabugogo commercial market; and this can be employed (Figure 9b).

Figure 9. (a) Green roof; (b) Permeable paving; (c) Channels; (d) Stone-filled infiltration trenches

Natural Water Resources Measures (NWRM) in general boost soil infiltration, delay overland flow, lower channel velocity, and raise evapotranspiration to change the hydrological cycle's rate and restore the landscape's ability to retain water. Both the frequency and the intensity of floods may be reduced because of these processes (Ribas et al., 2020). NFM focuses on working with the landscape to slow down and naturally store floodwaters. As an illustration of a nature-based solution, this study intends that Natural Flood Management (NFM) be promoted as a risk reduction method to help widespread sustainable flood risk management within Mpazi sub-catchment. NFM is one type of nature-based solution (NBS) that serves as an "umbrella concept" for a variety of ecosystem-related strategies for resolving societal issues (Wilkinson et al., 2019). This nature-based solution is one of many strategies being looked at internationally to lower flood risk. NFM encompasses a wide range of actions that change, repair, or make use of landscape elements to control flood risk. NFM seeks to manage floodwater sources and channels by collaborating with catchment-wide hydrological and morphological processes (Holstead et al., 2017). Moreover, it encompasses actions that "alter, restore, or use landscape features to manage flood (Figure 9c). Natural flood management strives to utilize and collaborate with natural processes to lower flood risk while also bringing about broader improvements in the environment and social and economic advantages in river catchments (Collentine & Futter, 2018) by using GIS to highlight the areas of attention and priority in Mpazi basin to implement this kind of nature-based solutions to reduce flood risks.

As a result, NFM may use a wide range of approaches, such as restoring upland mires, altering land use, planting trees, managing sediment, storing runoff, restoring rivers, and utilizing washlands (Holstead et al., 2017). Natural Flood Management (NFM) emerges as a sustainable and innovative approach to mitigate the risk of flooding in the highly flood-prone areas of the Mpazi sub-catchment. At its core, NFM involves the strategic deployment of ecosystem-based solutions that harmonize with the natural landscape. Afforestation along the river channel, a key component of NFM, entails the deliberate planting of trees and vegetation upstream. The roots of these plants act as natural barriers, absorbing excess rainfall and reducing surface runoff. This not only helps in stabilizing the soil but also aids in regulating the flow of water, preventing it from rapidly descending downstream of Mpazi channel. This overarches goal of NFM in the Mpazi sub-catchment is to restore and enhance watershed processes that have been adversely affected by human interventions. These interventions, such as deforestation and urbanization, have disrupted the natural balance of the ecosystem. By re-establishing these processes, NFM not only lessens the immediate flood risk but also promotes long-term resilience and sustainability in the face of climate change. As communities grapple with the escalating challenges of unpredictable weather patterns, embracing NFM offers a holistic and nature-based solution to foster a harmonious coexistence between human settlements and the surrounding environment (de Boer et al., 2015). By integrating these nature-based approaches with developed infrastructure, a more resilient and sustainable flood management system is created, safeguarding communities and the environment from the growing threat of floods.

5. Conclusion

Flooding can have a wide-ranging and severe impact on various sectors and communities. Human settlements and shelters are vulnerable to damage or displacement, threatening people's safety, and well-being. Health and nutrition, water and sanitation, education, agriculture, and infrastructure can all be disrupted or damaged, affecting the basic needs and services of the affected population. Small and medium-sized enterprises suffer losses and can struggle to recover. Moreover, flooding threatens human life, carries health risks from contaminants, and causes long-term environmental effects through erosion and habitat disruption. The economic impact can be substantial, affecting both the government and private sector. To address these issues, utilizing GIS for flood vulnerability assessment is essential. This approach helps identify high-risk areas and informs strategies for reducing the impacts through better preparedness, improved infrastructure, and sustainable land use planning. The flood vulnerability assessment in Mpazi sub-catchment reveals an urgent high-risk situation, with 80% vulnerability.

Priority recommended measures include nature-based solutions like wetland restoration, integrated GIS-based flood management, public awareness campaigns, and infrastructure development. Land use planning, coupled with continuous monitoring, provides a systematic framework for sustainable development. It enables the identification of high-risk zones, guiding informed decisions on urban expansion and infrastructure placement. Collaboration among stakeholders, including government bodies, non-governmental organizations (NGOs), and local communities, is fundamental to the success of these measures. Encouraging future research on Participatory GIS is recommended, it does not only advance scientific understanding but also strengthens community engagement, ensuring that local knowledge and perspectives are integral to the development and implementation of flood mitigation strategies. These measures collectively mitigate flooding risks, fostering sustainable development, and ensuring resident safety in flood-prone areas.

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Author Contributions

Patience Manizabayo, Laika Amani and Eugene Uwitonze: Literature review, field study, methodology, software, and data processing. **Isaac Nzayisenga and Sabato Nzamwita:** Revision, data validation, visualization and interpretation. **Nzayisenga Isaac, Hyacinthe Ngwijabagabo and Katabarwa Murenzi Gilbert:** Reviewing, editing, and final draft.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

Research and publication ethics were complied with in the study.

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