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Flood vulnerability assessment using geographical information system: Case study of Mpazi Sub-catchment, Kigali

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Abstract

Floods in the Mpazi sub-catchment pose significant and recurring threats to the community and environment. This study utilized GIS technology to assess flood vulnerability by integrating spatial data on land use, elevation, and rainfall patterns. The results revealed a high susceptibility to flood hazards, particularly during the rainy season. This information is invaluable for stakeholders in formulating effective flood management strategies to mitigate the devastating impact of these recurrent floods on society and essential infrastructure. The study identifies the most vulnerable areas: 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). Infrastructure, such as residential and commercial buildings, is impacted by flooding. This study offers valuable insights for decision-makers and stakeholders, supporting the development of effective flood management plans in the Mpazi sub-catchment.

1. Introduction

Globally, climate change makes many people highly vulnerable to natural disasters and other environmental changes (Wali et al., 2013). This is because the climate has changed and is continuously changing globally. As a result, there are natural increases in the frequency and severity of natural disasters (Hu et al. 2017). The most common natural disasters occur when the river channel receives much more water than it can (Andrews, Babb, and Barber 2017). Excessive rainfall results in the rivers rising, and a flood develops because the river cannot handle the extra water, causing flooding everywhere along the river's path. Excessive rainfall results in the rivers rising, and a flood develops because the river cannot handle the extra water, causing flooding everywhere along the river's path. 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).

Nyabugogo watershed, particularly the Mpazi Sub catchment that is the focus of our research, has experienced flooding in several incidents. This is mostly because the 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. 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. 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 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.

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Vulnerability refers to the degree of loss to a given element at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage) damage (United Nations, 2018). In the context of flooding, vulnerability refers to the degree to which elements at risk are susceptible to the negative impacts of flooding, such as property damage, displacement, or loss of life. Various factors can influence vulnerability, including socioeconomic status, geographic location, infrastructure, and environmental conditions (De Brito, Evers, and Delos Santos Almoradie, 2018). According to (Hoque et al. 2019), the vulnerability is expressed using the Equation (1):

$$\textit{Vulnerability} = (\textit{Exposure}) + (\textit{Resistance}) + \textit{Resilience} \quad (1)$$

This study aims to bridge a critical knowledge gap by utilizing GIS-based analysis, specifically the GIS-AHP method, to map flood-prone areas within the Mpazi sub-catchment comprehensively. Past research has highlighted the inadequacy of previous GIS technology in this regard.

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. 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.

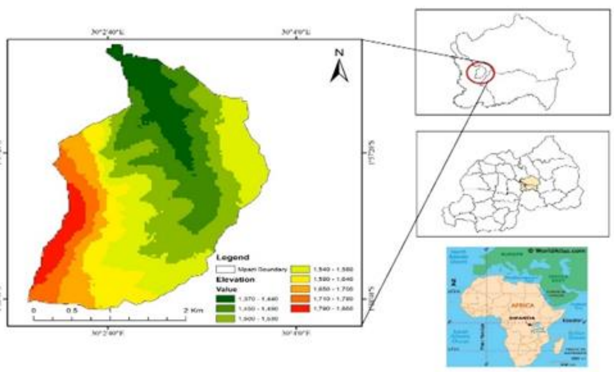

Figure 1. Study Area

Figure 2. Mpazi sub-catchment downstream (Source: Photo from Google Earth Pro, 2023)

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.

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).

Another important flood risk factor is distance from the river channel. 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). 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 level >2-7 tend to be wet and more vulnerable to risk compared to areas with low wetness (Figure 3d).

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. Higher elevations offer natural protection from flooding.

Table 2. 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
Topographical Wetnex Index	Level	2 - 7	-1 – 1	-3 - -2	-5 - -4	-8 - -6	0.09
Elevation	m	>1370 – 1490	1500 – 1560	1570-1650	1660 - 1750	1760 - 1860	0.1
Distance from River	m	<129	>130 – 257	>258 – 386	>387 – 515	>516 - 644	0.225

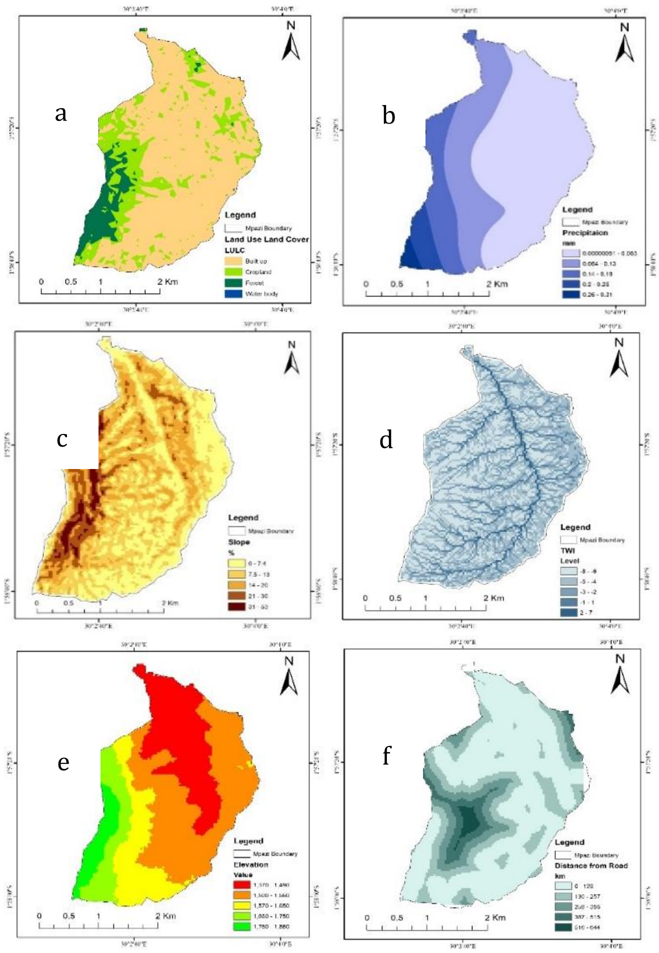

Figure 3. Flood risk criteria maps (a) Land Use Land Cover (b) Precipitation (c) Slope (d) Topographical Wetness Index (e) Elevation (f) Distance from River

3. Results

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) as shown in Table 3. According to the field survey, infrastructures such as residential houses, trading centers, roads and bridges are frequently affected by flooding.

Table 3. Flood risk areas in Mpazi Sub-catchment

Flood Risk Classes	Area (Km^2)	Rate (%)
Very Low	105.77	11.9
Low	45.51	5.12
Moderate	268.62	30.22
High	115.73	13.02
Very High	353.34	39.74

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 as shown in Figure 4 (a). 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 as shown in Figure 4 (c).

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, while NFM focuses on working with the landscape to slow down and naturally store floodwaters. 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.

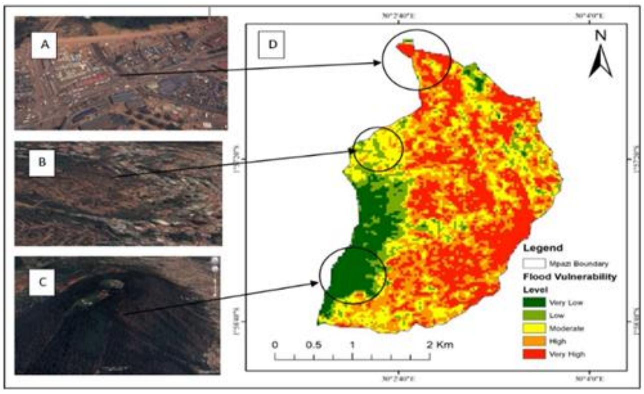

Figure 4. Flood Risk Map of Mpazi Sub-catchment

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.

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