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Geospatial Assessment of Urban Flood Susceptibility Using AHP-Based Multi-Criteria Technique: Case Study of Musanze, Rwanda

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Abstract

Over the last decade, flood events in the northern and western urban areas of Rwanda have increased due to anthropogenic activities and the effects of climate change. This study aims to use the Analytic Hierarchy Process (AHP) geospatial multi-criteria technique to identify flood susceptibility areas and exposed assets in Musanze City. Seven factors were considered such as Topographic Wetness Index (TWI), Rainfall, Land Use Land Cover (LULC), Slope, Soil Texture, River, and Digital Elevation Model (DEM) to create a flood susceptibility map with 5 classes (from very low to very high). To validate the final map, 26 GPS points were collected from areas with a history of flooding, and the susceptibility classes were compared. Results showed that 33% of the area (~2367 ha) was classified as high to very high risk, 23% (~1645 ha) was classified as moderate, and 44% (~3113 ha) was classified as low and very low susceptibility. The study also identified physical infrastructure and land use exposed in high and very high flooding areas, including 24 schools, 2 markets, and 1 health facility, 18668 km of roads, and 3400 buildings that are highly exposed to flooding. The applied methods in this study are useful for urban planners and government officials in developing flood mitigation policies, strategies, and plans.

Keywords: Flood Susceptibility, Analytical Hierarchy Process (AHP), Geospatial multi-criteria technique, Musanze City, Rwanda

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1. Introduction

Floods are regarded as one of the most devastating hydro-meteorological disasters since they frequently cause massive monetary and environmental destruction, as well as deaths (Hussain et al., 2021). Floods are also the most serious threat to social security and sustainable development, affecting an estimated 20–300 million people each year (Dewan, 2013). Flash floods have a significant impact on cities rather than on rural areas due to higher population densities and concentrations of economic activity. Flooding in cities is typically caused by extremely high flows from extreme regional meteorological disturbances or even by local high-intensity thunderstorms that occur over parts of the urban area (Jegatheesan et al., 2019; Herrmann & Bucksch, 2014). Due to the presence of extensive impervious areas and inefficient drainage systems, with limited discharge capacity of urban channels and rivers, urban areas are at substantial risk of severe flooding (Danumah et al., 2016). According to Herrmann & Bucksch (2014), a lack of careful planning coupled with uncontrolled urbanization will intensify the trend of cities becoming more vulnerable to natural disasters like flooding. Flood risk assessment and zoning are critical in urban environment discussions for the sustainable development of human settlements due to their development on river margins, flood plain margins, and attention to hydrological and dynamic conditions of rivers, which increase the risk of flood and endanger lives and infrastructure (Sepehri et al., 2019). The need for geospatial assessment of disasters has become increasingly urgent in order to effectively develop disaster mitigation plans in urban areas. (Nugraha et al., 2018). Geographical information System (GIS) and Remote sensing techniques are used for generating flood susceptibility maps, these techniques are extremely helpful in detecting the spatial aspect of floods for management activities (Chukwuma et al., 2021). There are three types of geospatial approaches used in flood risk management: flood mapping, damage assessment, and flood risk and susceptibility assessment (Dewan, 2013). A common technique for risk and Susceptibility assessment is to create a spatial index of a risk or susceptibility level (Tomaszewski, 2014). However, to address some of the drawbacks of using GIS in flood assessment and susceptibility mapping, Multi-Criteria Decision Making (MCDM) Models such as the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) have been integrated with GIS methodologies (Costache et al., 2020; Ngwijabagabo et al., 2021) (Cost ache et al., 2020). Rwanda has been experiencing flooding since the 2000s due to the dramatically increasing rainfall in many parts of the country (GoR, 2007). According to the report of the International Federation of Red Cross and Red Crescent Societies (IFRC, 2021), starting from November 2019 heavy rainfall has affected many parts of Rwanda and triggering flooding with the overflow of rivers and having a significant impact on human development, property, infrastructure, and the environment. Floods and landslides wreak havoc on Rwanda's urban infrastructures, especially in transportation sector and some districts are struggling to find long-term solutions (Nkurunziza, 2022). It is also reported that the major environmental threats in Musanze District are landslides and flooding (RHA, 2020). Moreover, Musanze as secondary city is frequently afflicted by heavy rainfall in the volcanoes area, potentially causing overflow of classic torrential rivers such as Rwebeya, which flows from the north to the south of the city, Muhe, and Susa River, which are located in Musanze's western urban area (WGR, 2018). Despite the fact that the city's urbanization level is expected to reach 35% by 2024, with an annual growth rate of about 7.7% (GoR, 2015), Musanze City still lacks a flood risk and susceptibility mapping to facilitate the future urban planning. In addition, a more localized flood

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risk and susceptibility is still uncommon in Rwanda's urban areas that are more affected by flooding due to the effects of urbanization and climate change. Furthermore, in many flood assessment studies only river floods were considered in a few catchments, leaving behind flash floods that are affecting major urban areas of Rwanda (MIDIMAR, 2015). Therefore, this paper tried to address the above mention gaps using geospatial tools to assess the level of flood risk and susceptibility in a more localized context.

2. Materials and Methods

2.1. Study Area Description

Musanze City is located in the Northern Province, northwest of Kigali at a distance of approximately 110 km (Figure 1). The city is situated in Rwanda's most mountainous region, which is home to the largest part of the Volcanoes National Park. Musanze City is one of Rwanda's six secondary cities. Within the Northern Province, it has the highest urban population and is second only to Kigali City. According to the latest figures available from the Ministry of Statistics, 28% of the total district population is urban (Musanze City), while the national average is 18% (NISR, 2012).

The city has a high-altitude tropical climate, with an average temperature of 20ºC. Rainfall is generally abundant, reaching up to 1,800 mm per year. The hydraulic network in the city is formed by temporary torrents and permanent watercourses. The main torrents passing through the city boundary are Susa, Muhe, Rwebeya, and Cyuve. The permanent watercourses within the city are Mpenge Spring and Kigombe Spring, with flow rates of 2.3 m^3/s and 0.7 m^3/s, respectively, originating from the water table (Zimmerman, 2012). Most of the rivers passing through Musanze City experience overflows, causing flooding due to the lack of channel capacity (WGR, 2018).

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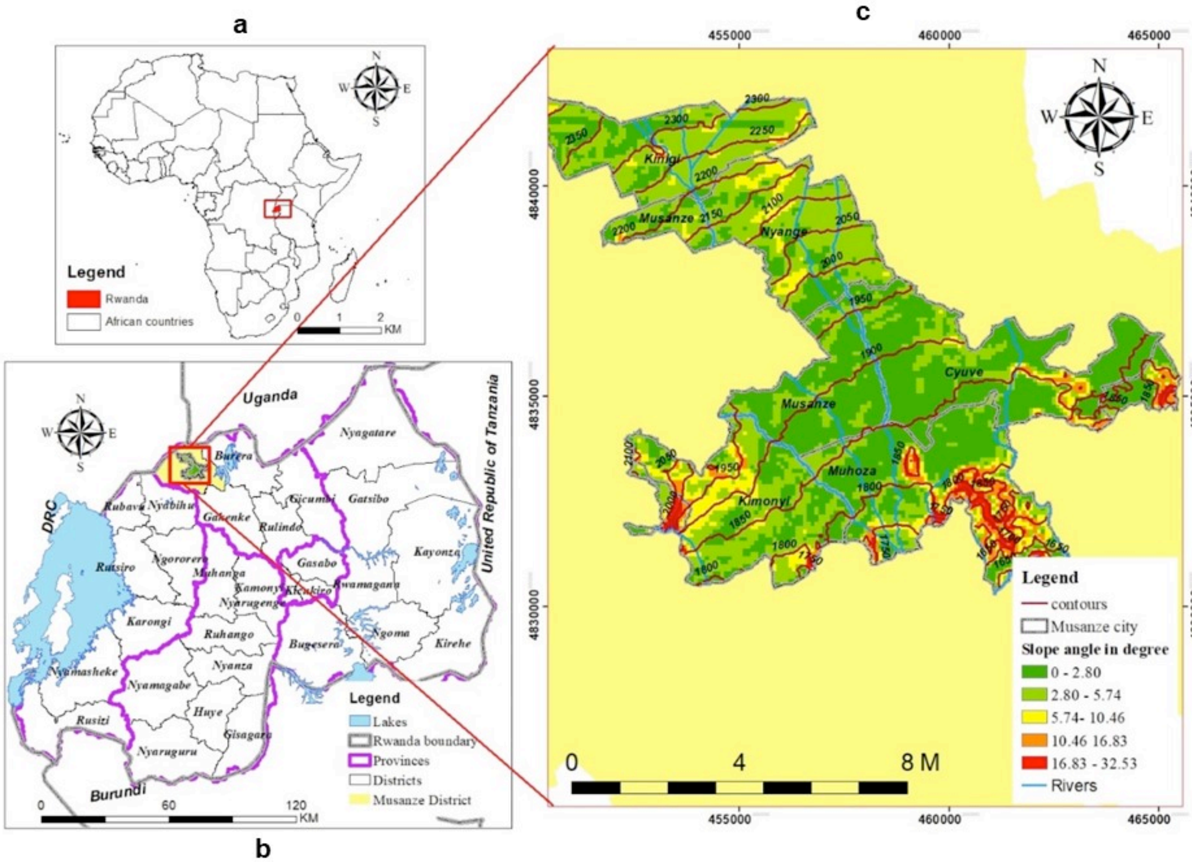

Figure 1: Localization of the study area **(c)**; Rwanda (**b**); and Africa **(a)**

2.2. Data Source and Processing

To achieve the study's objectives, various data sources, including administrative boundaries (Africa, Rwanda, and Musanze City), land use, rainfall, DEM, soil type, and rivers, were collected. Both primary and secondary data sources were utilized in this study. The factors used were identified through a literature review technique. As the factors did not have the same level of impact on the flood-generating mechanism in the area, weights were assigned to each factor. The Analytical Hierarchy Process (AHP) was used to assign weights, with input from Musanze District's agricultural and natural resources unit. The experts assigned weights based on the criteria's significance. GIS and mapping tools were employed to process the data and produce maps.

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Table 1: Source of Data

No	Layers data	Format /Spatial Resolution	Source of data
1	Administrative boundary	Vector data	The administrative boundary layers were obtained from the updated administrative boundary from the following link: https://www.diva-gis.org/gdata. The Musanze city administrative layer was derived from the Global Green Growth Institute (GGGI) and Rwanda Housing Authority's revised master plan for six secondary cities, which was elaborated in 2020.
2	Rivers	Vector data	The Layer of Rivers was created in 2008 by the Rwanda Environmental Management Authority (REMA).
3	Rainfall		The Centre for Geographic Information Systems and Remote Sensing provided the rainfall data used (CGIS - UR). Interpolation of data from three meteorological stations in Musanze City was used to build a continuous raster rainfall data set for our study area.
4	Land cover	Raster data/10M*10M	Free global 2020 land use /land cover layer was acquired through ESRI Sentinel-2 land use/ land cover downloader. https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2
5	Soil Texture	Vector data	The soil texture data layer was created using MINAGRI's Rwanda soil map layer
6	DEM (10m of resolution)	Raster data/ 10M*10M	DEM layer was acquired from Centre for Geographic Information System and remote sensing at the University of Rwanda.
7	Roads, Schools, Markets, and health facilities	Vector data	Infrastructure data provided by Musanze District One Stop Center.
8	Building footprint	Vector data	The source of the data is the 2015 Houses Survey conducted by the National Institute of Statistics Rwanda

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The procedure and approach used to determine the study area's susceptibility to flooding are described in the following methodological flowchart in Figure 2, which depicts many stages taken to accomplish the study's goal.

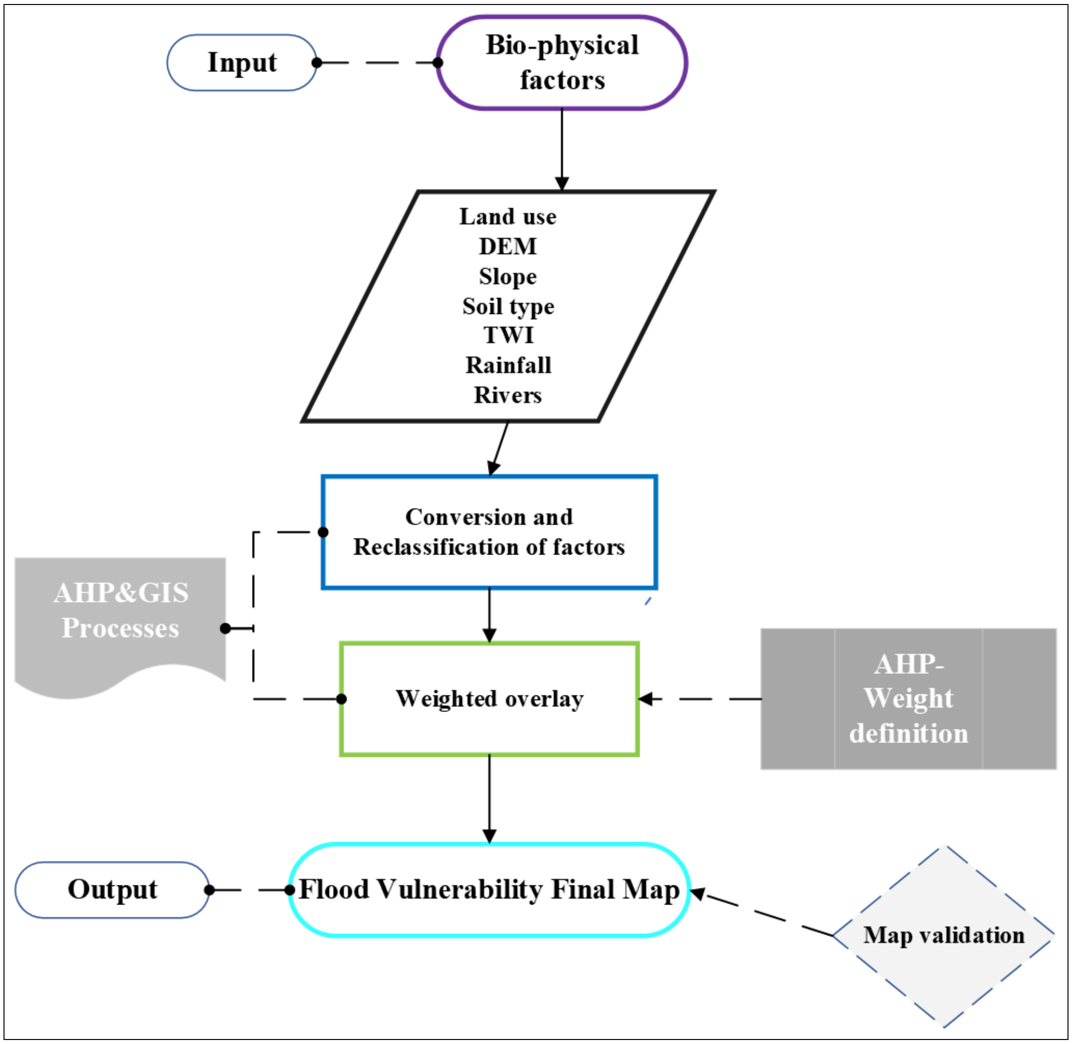

Figure 2: Methodological Flowchart

The methodological flowchart presented in Figure 2 illustrates the process followed in this study. The first step was to collect data on the biophysical factors that influence flooding in Musanze's secondary city. The variables of each factor were then classified, as shown in the map in Figure 3. After that, the factors were weighted based on their level of influence, using expert judgments from Musanze District's agricultural and natural resources unit. An AHP priority questionnaire link was sent to them, as described in Section 2.2.2. Once the weighting and calibration of the

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consistency ratio (Table 2) were completed, a weighted overlay of all factors was performed, resulting in the final vulnerability map as output. In the final stage, the map was validated by collecting 26 GPS points from areas with a history of flooding and comparing the susceptibility classes. Finally, the vulnerability map was used to identify different assets at risk.

2.2.1. Analysis of Biophysical Flood Susceptibility Factors

The effective factors are parameters that allow the assessment of the risk of flooding. However, it is never easy to identify parameters for flood susceptibility mapping that everyone agrees on (Kia et al., 2012; Tehrany et al., 2014; Samanta et al., 2018). Therefore, to produce a flood hazard susceptibility layer, seven biophysical factors were identified using an intensive literature review on flood susceptibility assessment. The identified main influencing biophysical factors, also called geo-environmental factors, are as follows:

Topographical wetness: The TWI map depicts the effect of topography on the quantity of wet levels that generate runoffs, and it is a useful measure for determining a watershed's flood potential (Ali et al., 2019). TWI is a key runoff predictor because surface runoff from storm rainfall is crucial for anticipating floods that are rapid, showy, and of short duration (Costache et al., 2020). The TWI runoff predictor was calculated using the DEM and different processes in Arc GIS. The final TWI map was generated using the following equation adapted from the original form of the formula (Beven & Kirkby, 1979):

$$\boldsymbol{TWI} = \boldsymbol{Ln}\left(\frac{\boldsymbol{flow\ accumulation\ scaled}}{\boldsymbol{Tan\ slope}}\right)$$

The use of TWI was found to be crucial in urban flood assessment because it is an important tool to study urban surface runoff caused by a lack of infiltration surface in urban areas (Samanta et al., 2018).

Land use: Land use is believed to influence the infiltration capacity and runoff coefficient of water (Rahmati, Pourghasemi, et al., 2016). Land use influences surface roughness, which controls surface flow characteristics such as depression storage capacity, velocity etc. (Bahremand et al., 2007; Rahmati, Zeinivand, et al., 2016). Long-term flood control necessitates an integrated approach that includes land use planning and green infrastructure to restore vegetative cover and thereby reduce peak discharges and the amount of stormwater flowing into storm drains (Owusu-Ansah et al., 2019). Land uses in our study area are divided into seven major groups: water, forest, grass, crop, shrub, settlements and buildings.

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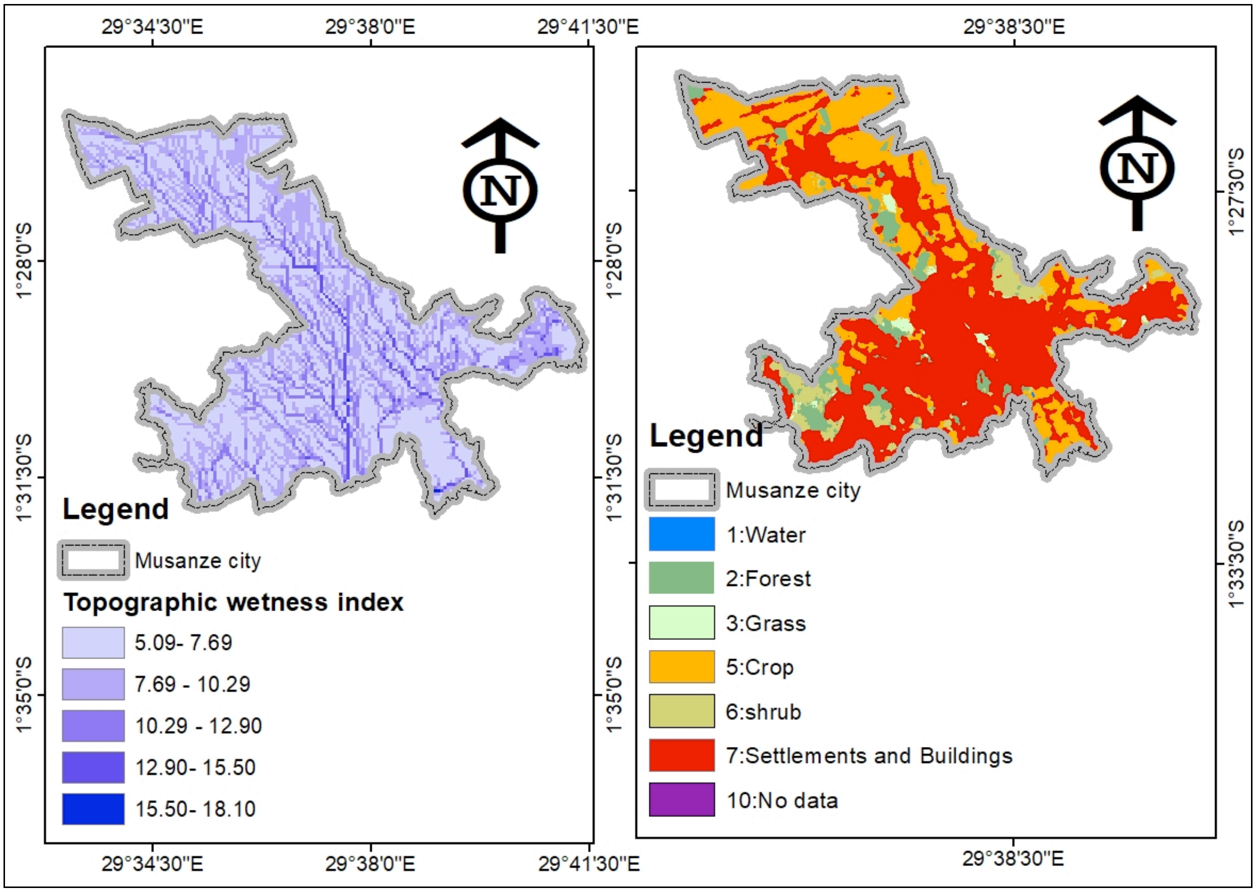

Figure 3: Topographic Wetness Index (*left*); Land Use (*right*).

Percentage of clay in soil: The amount of clay in the soil has a significant impact on flood analysis. A high clay-content soil has a lower infiltration capacity, which increases runoff or overland flow than a low clay-content soil (Ali et al., 2019).

Rivers: Rivers have a crucial influence in generating floods in urban areas. During seasons of prolonged rainstorms, rivers naturally flood out excess floodwaters slowly or instantly and intensely into the nearby riverside landscapes, exposing the area to riverine flooding (Owusu-Ansah et al., 2019).

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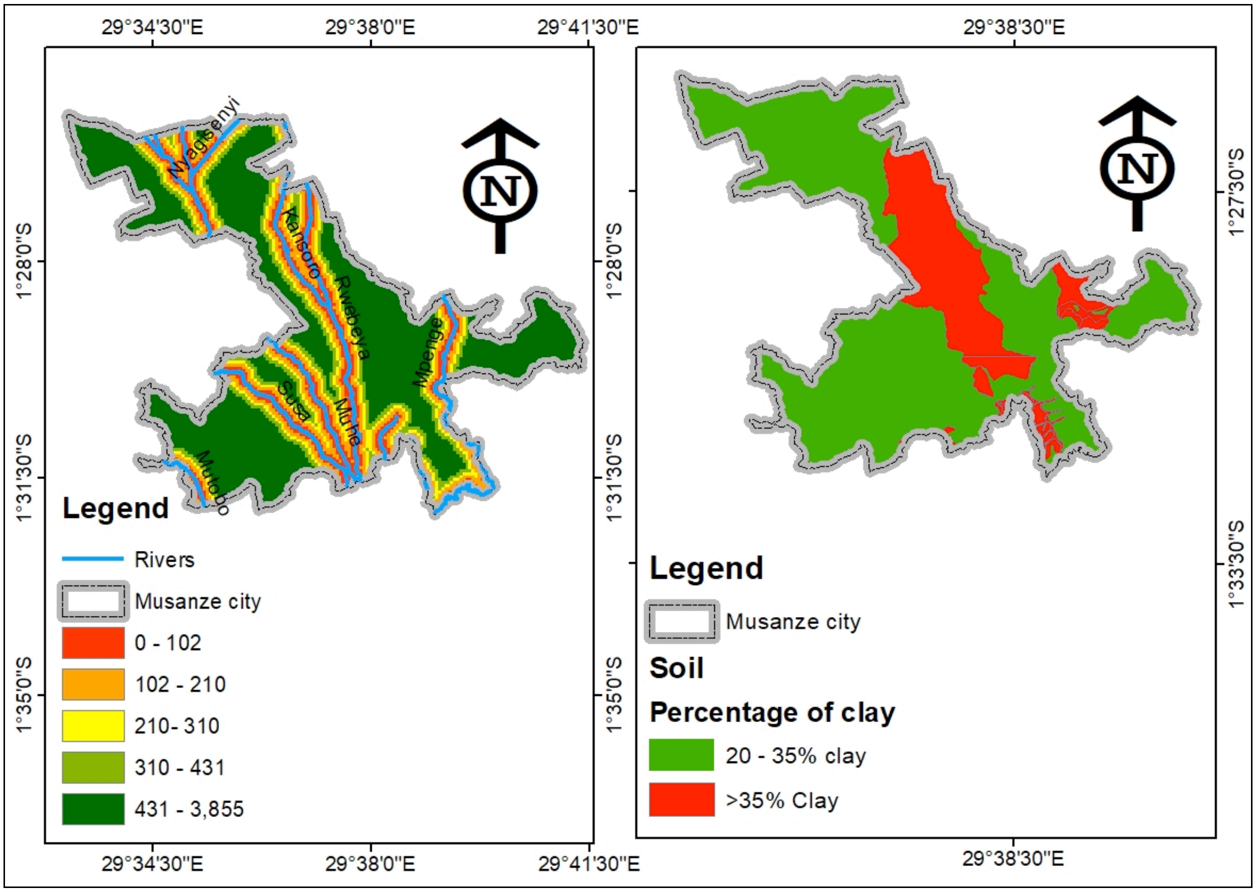

Figure 4: Proximity to Rivers (*left*); Soil content (*right*).

Elevation: The elevation has a considerable impact on the direction and volume of surface runoff and subsurface drainage velocity, low-lying plain areas are more susceptible to flooding due to as it rapidly flows from upland to flat plain areas (Tayyab et al., 2021).

Slope: Slope is among the important causative factors that contribute to floods in urban areas (Wang et al., 2022). This is in relation to the influence of slope on water flow characteristics such as velocity and discharge (Roy et al., 2021).

Rainfall: The trend and patterns of urban floods have gotten increasingly and in the last 50 years as a result of climate change and other human-induced variables (Reay et al., 2007). Therefore, as the effects of climate change have affected the intensity and frequency of rainfall, this factor is significant in assessing the occurrence of floods (Chukwuma et al., 2021). According to Tayyab et al.(2021), flooding usually occurs as a result of significant rainfall. The trend and patterns of urban floods have increased in the last 50 years as a result of climate change and other human-induced variables (Reay et al., 2007).

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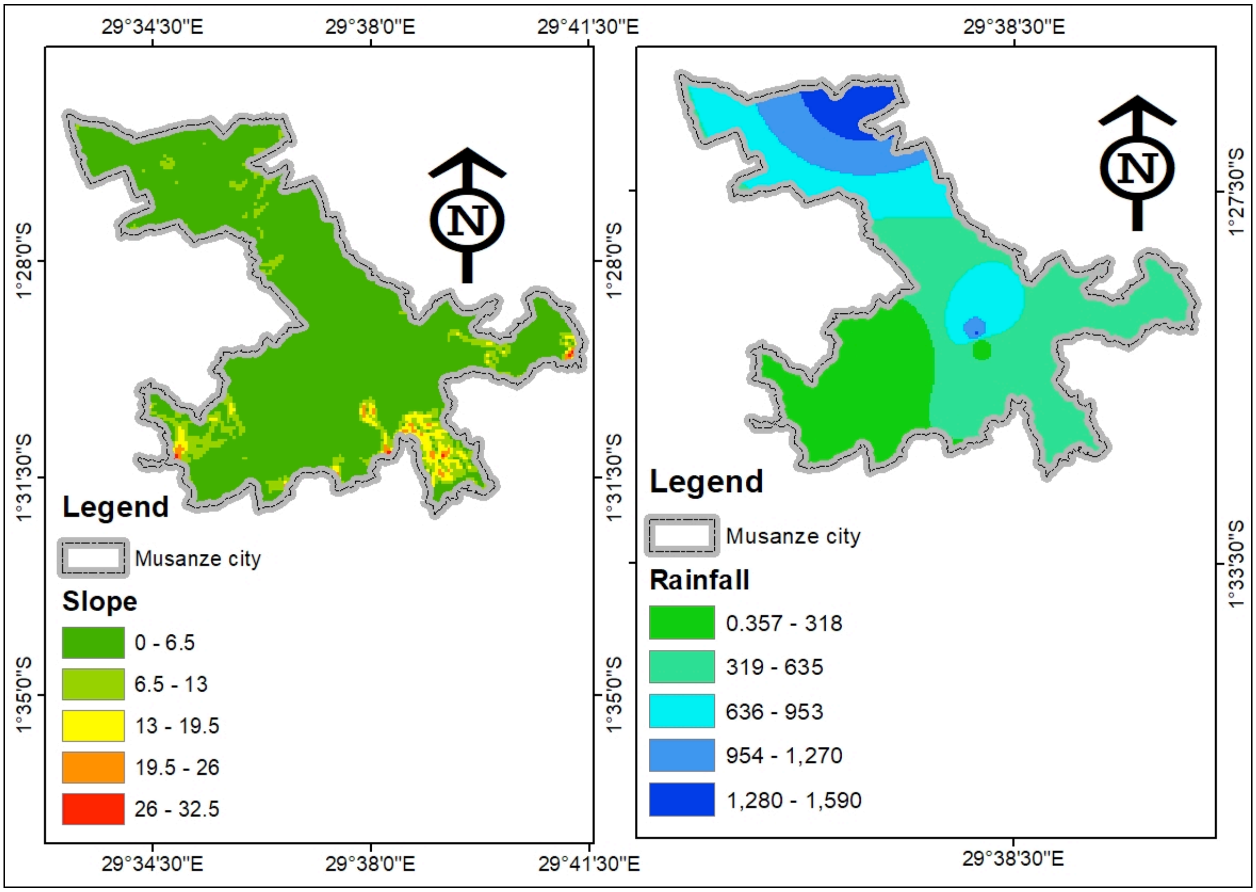

Figure 5: Slope *(left)*; Rainfall *(right)*.

The biophysical factors depicted in Figures 3, 4, and 5 were classified using the Spatial Analyst toolbox in ArcGIS. These parameters were rated into classes of susceptibility to flooding, ranging from very low to very high, as shown in Table 3.

2.2.2. Process of Analytical Hierarchy (AHP)

The analytical hierarchy process (AHP) is one of the most widely used and effective methods in disaster modeling, such as flood monitoring, mapping, and problem analysis(Hussain et al., 2021; Nsangou et al., 2022; Samanta et al., 2018). By comparing factors two by two using a matrix, Saaty's AHP (Saaty, 2008) provides objective calculation of weights or weighting coefficients. The first stage is to identify the choice problem and use the Saaty scale from 1 to 9 to rank the relative relevance of the factors. This step was completed using expert judgments from Musanze District's agricultural and natural resources unity. With the judgments from the experts, the weighting coefficient was calculated using the eigenvectors of the factors compared to one another (Table 2). The final stage entails establishing attributes in order to check the logic of the judgments. Because the AHP method is based on individual judgment, personal preferences, and subjectivity are present in both expert and user assessments (Hussain et al., 2021). As a result, there's a greater chance of developing unreliability when it comes to

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completing them. For this type of indecision, the researcher does a consistency check to see if the comparing judgment is reasonably consistent or if the exercise should be repeated before continuing. According to Saaty (2006), the consistency ratio of the matrix that is considered as acceptable is about 10%. The consistency ratio (CR) was calculated (Table 2). The results indicated that the CR was approximately 5.5% which implies that the prioritization of the matrix was correct regarding the expert's judgment score that was assigned to the factors. All the processes and calculations were completed using AHP priority calculator.

Table 2: AHP Weight Results

	Category	Rank	Weight (%)
1	TWI	2	18
2	Slope	3	15
3	Soil properties	5	12
4	River	1	19
5	DEM	7	10
6	Rainfall	4	14
7	LULC	6	12
	Number of comparisons = 21		
	Consistency Ratio (CR) = 5.5%		

2.2.3. Factors Layers Standardization, and Classification

The independent criteria, which are factors influencing flooding in flood risk mapping, have been standardized as shown in Table 3. The selected factors shown in Figures 3, 4, and 5 - namely, topographic wetness index (TWI), rainfall, land use/land cover (LULC), slope, soil texture, river, and DEM - have been developed with their subclasses classified into five risk classes (1: very low; 2: low; 3: moderate; 4: high; and 5: very high).

Table 3: Standardized factors

Weight	Unity	Susceptibility classes	Ratings naming classes
		Topographic wetness index	
18	Level	5.1 - 7.7	1:Very low
		7.8 - 10	2:Low
		44847	3:Moderate
		14 - 16	4:High
		17 - 18	5:Very high
		Rainfall	

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14	mm	1200-1400	3: Moderate
		1400-1600	4:High
		>1600	5:Very high
		LULC	
12		Water	1:Very low
		Forest	2:low
		Grass & shrub	3: Moderate
		Crop	4:High
		Settlements and Buildings	5:Very high
		Slope	
15	%	0-6.5	1:Very High
		6.5-13	2:High
		13-19.5	3:Moderate
		19.5-26	4:Low
		26-32.5	5:Very low
		Soil texture	
12	% of clay	20 - 35% clay	5:Very Low
		>35% Clay	1:VeryHigh
		Proximity to Rivers	
19	m	0 – 102	5:Very high
		102 – 210	4:High
		210-310	3:Moderate
		310-431	2:Low
		431 - 3,855	1:Very low
		Elevation	
10	m	1,642 - 1,802	5:Very high
		1,802 - 1,962	4:High
		1,962 - 2,122	3:Moderate
		2,122 - 2,282	2:Low
		2,282- 2,443	1:Very low

The results of classification and weighting in Table 3 were utilized in the creation of the final overlay map. The table provides standardized factors along with their respective weights, susceptibility classes, and ratings naming classes. The classifications and ratings were used to determine the level of flood risk in the study area and to generate the final overlay map.

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3. Results and Discussions

3.1. Flood Susceptibility in the Study Area

The final susceptibility map (Figure 4) reveals that 2367 ha (33%) of the study region were classified as having a high to very high risk, while 1645 ha (23%) were classified as moderate, and 3113 ha (44%) were classified as having low or very low susceptibility. Most of the areas with high and very high susceptibility are located near the main river channels, such as Rwebeya, Muhe, Susa, Cyuve, Mpenge, Mutobo, Kigombe, Kansoro, Nyonirima, Kampanga, Nyagisenyi, Mukungwa, and Mutobo, which pass through the city boundary. These high and very high susceptibility areas are mainly located in urbanized areas with poor drainage, less clayed soil, and high rainfall intensity. This situation was also observed in Kigali, according to Mind'je et al., (2019). Accelerated urbanization, in association with extreme weather, poor drainage, reduced infiltration that contributes to high runoff, rapid structural growth, and the presence of unstructured and poor urban settlements, has exacerbated the problem of flooding in urban areas of Rwanda, including Kigali city.

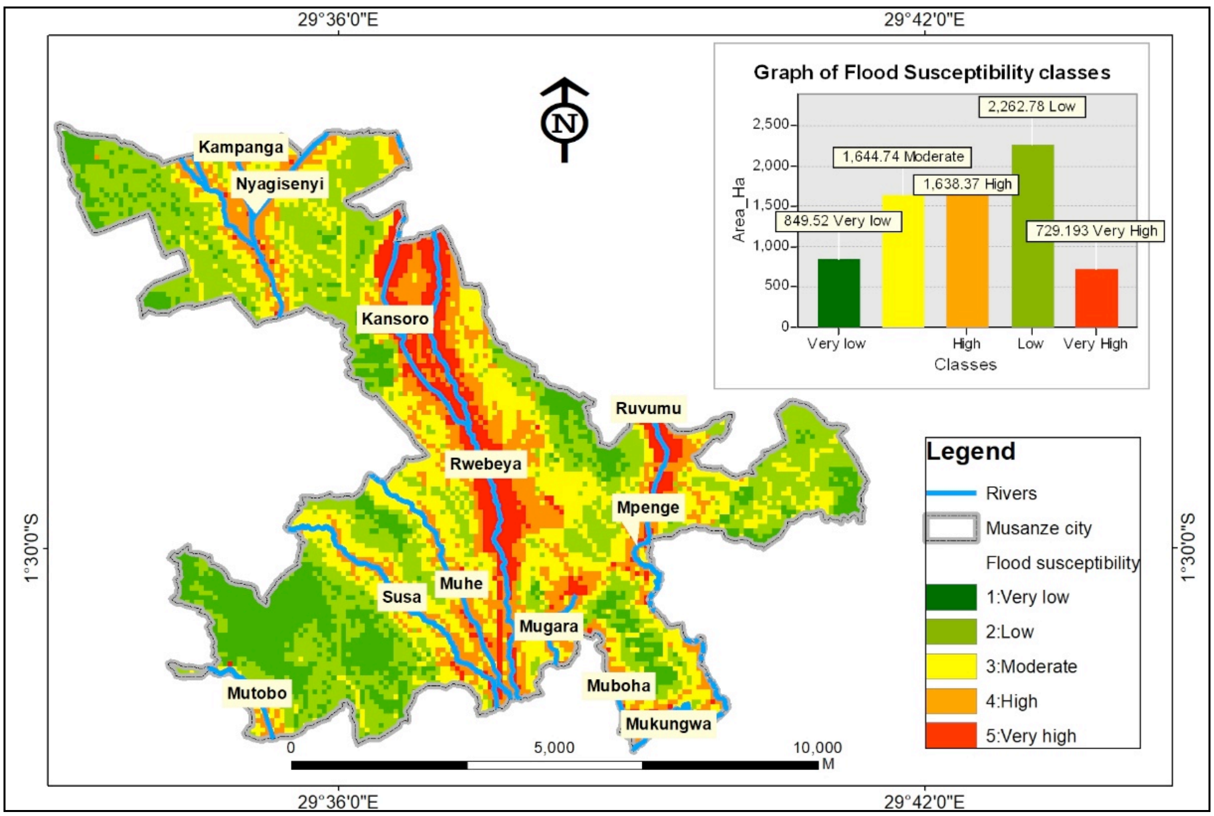

Figure 6: Flood Susceptibility map

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3.2. Exposure of Main Infrastructures

Urban infrastructure is a valuable resource for communities, governments, and the business sector (Yoga et al., 2020). According to Park & Lee, (2019), the red zone for flood risk is mainly found in areas with important infrastructure in the core business area, where many facilities, including public institutions that play vital roles in the city, are located. Identifying infrastructure at risk is an important part of the hazard risk assessment process (Schelhorn et al., 2014). Flood hazard maps are basic tools for preparedness and mitigation and are crucial in establishing insurance policies for properties in the United States and some European countries, such as the United Kingdom (Herrmann & Bucksch, 2014).

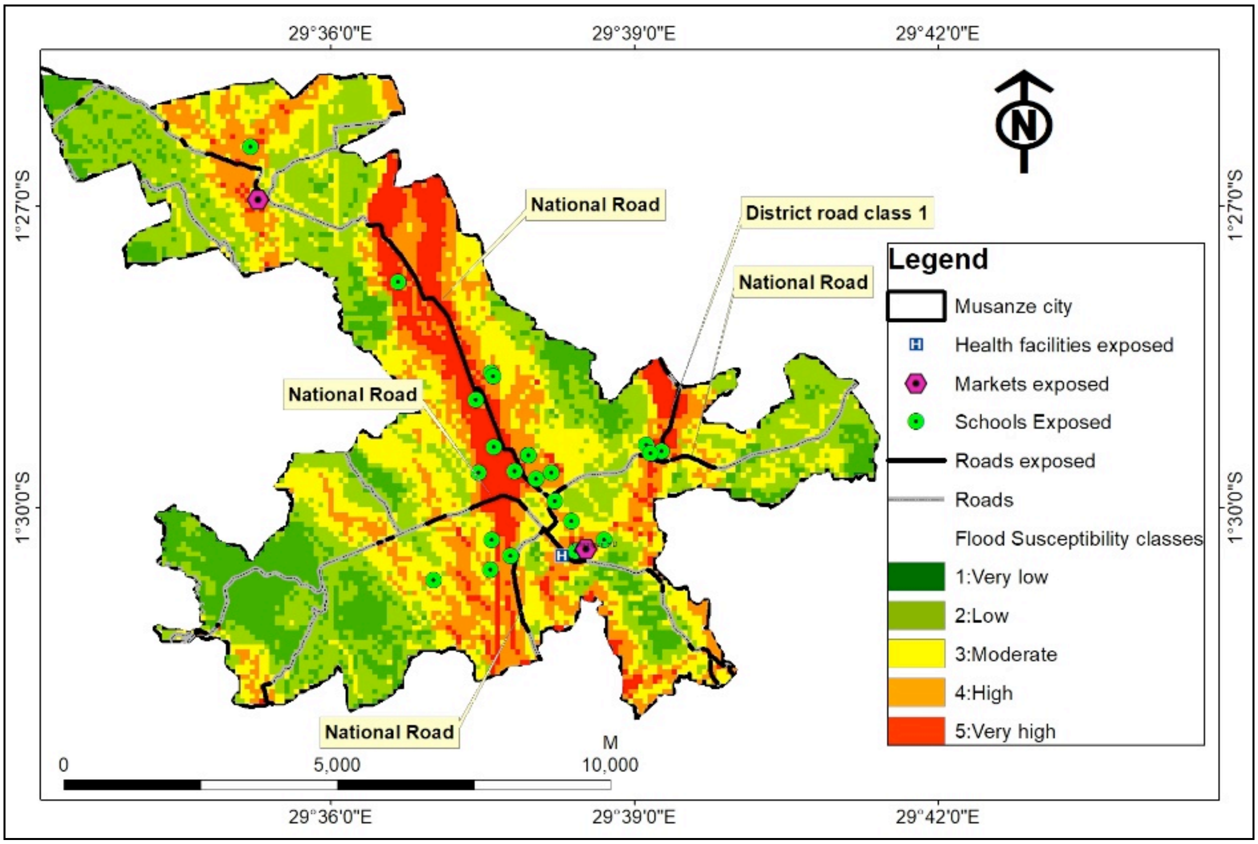

Figure 7: Public Infrastructures more exposed to flooding

The identification of exposed important infrastructures such as schools, hospitals, buildings as well as main roads linking the districts was identified in Figure (8). It was found that 18668 km of roads are exposed to flooding; this was mainly the national roads and district road of class 1. Two district markets were found to be exposed; the Kinigi Market located in the northern part of the city has been frequently inundated in the past due to its proximity to Muhe River which overflow in high rainfall season. 24 schools out of 51 were found to be exposed to the flooding which means that 47% of all schools located in the city boundary are at risk of being flooded.

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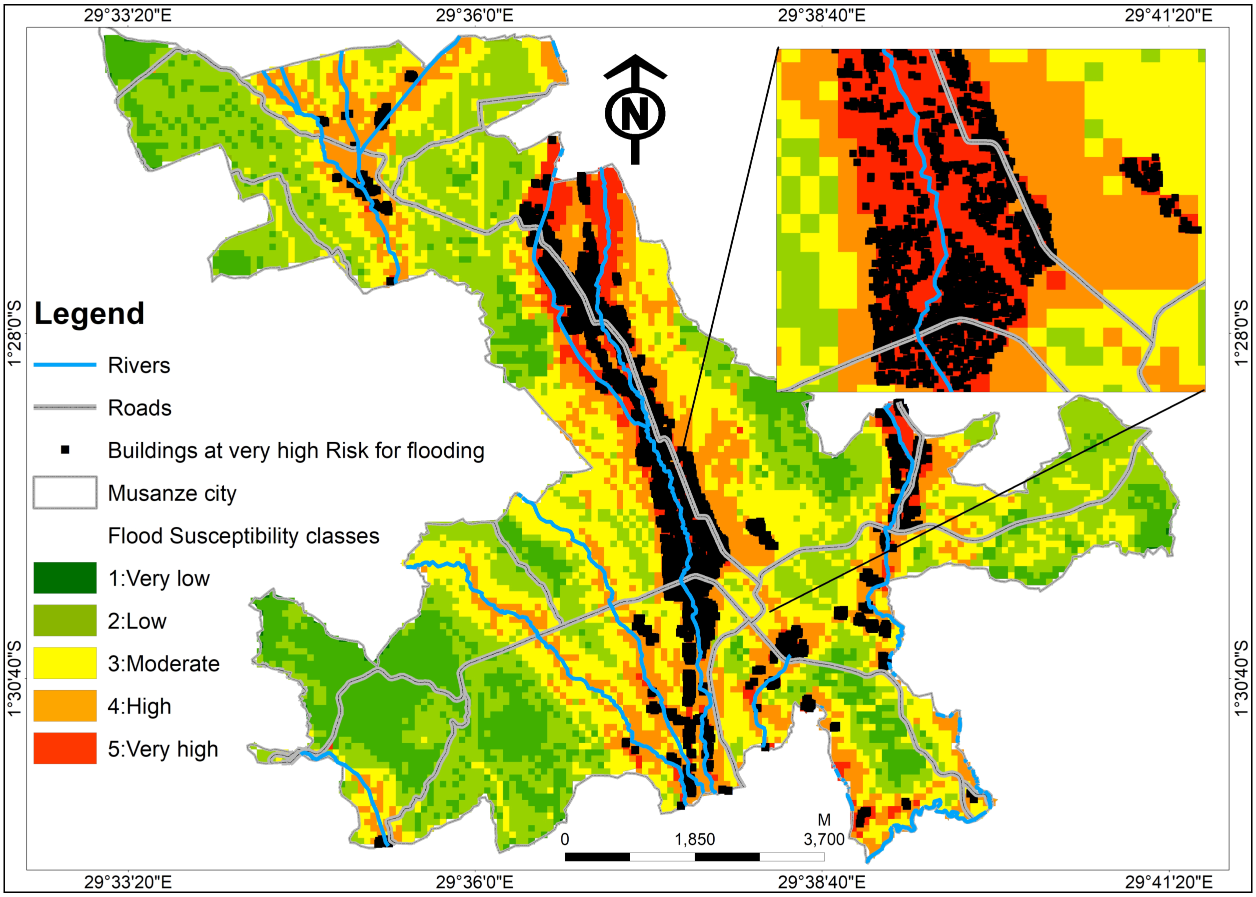

Figure 8: Building exposed to very high-risk flooding

Figure 9 displays a map that highlights a significant number of buildings, totaling approximately 3400, that are at a very high risk of flooding. The majority of these buildings are located in flood-prone areas around the Rwebeya and Kansoro Rivers, as well as along the National Road paved NR 18. It is crucial to address the potential dangers posed by these flood-prone areas, as they pose a threat to the safety and well-being of the people living in these buildings.

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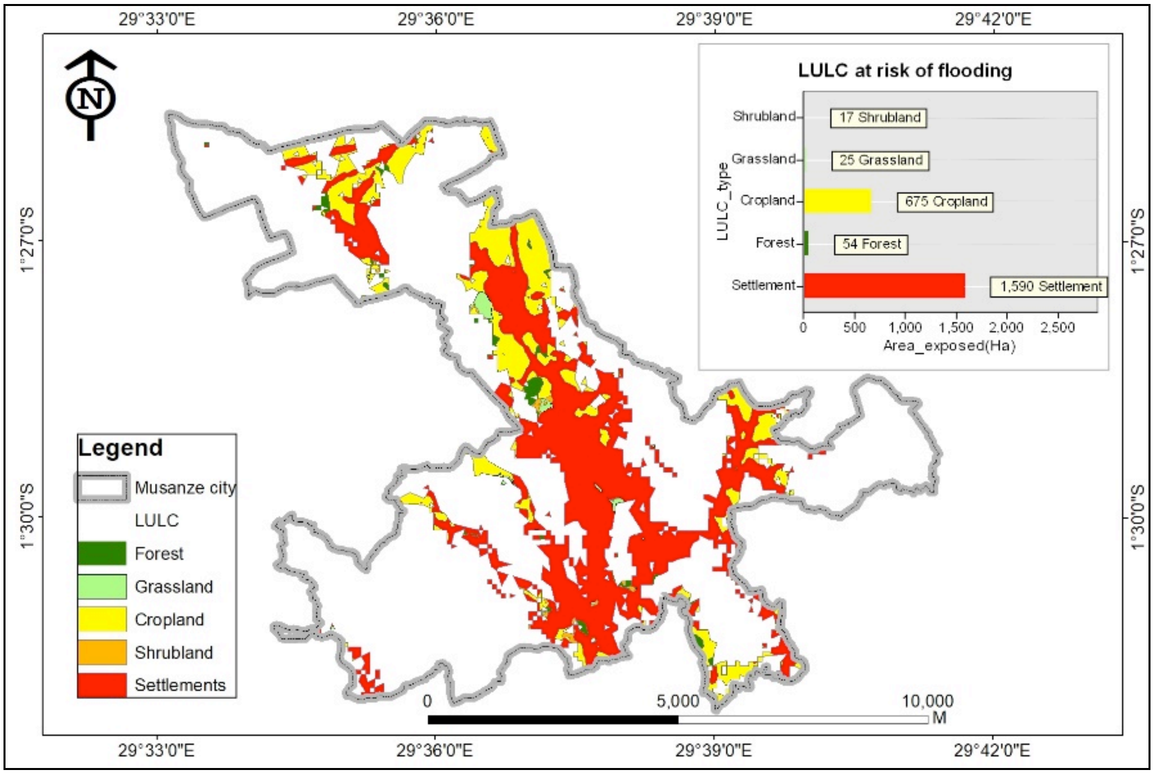

Figure 9: LULC exposed to high and very high risk to flooding

In terms of land use land cover in the study area, settlements occupy a considerable area of 1590 ha that is exposed to high and very high risk of flooding, followed by urban cropland covering 675 ha that is also exposed to high and very high risk of flooding, as shown in Figure 10.The presence of settlements occupying a significant area of 1590 hectares in the study area that are exposed to high and very high flood risks has significant implications for the safety and well-being of the residents living in these areas. This high exposure to flooding increases the likelihood of damage to property, loss of livelihoods, and even loss of life. In addition, flood-prone settlements can also cause significant economic and social disruption in affected areas. The exposure of urban croplands covering 675 hectares to high and very high flood risks also has significant implications. Flooding can cause damage to crops, which can lead to food shortages and economic losses for the farmers who depend on them for their livelihoods. In addition, the damage to agricultural infrastructure, such as irrigation systems, can lead to longer-term impacts on the productivity of the area.

3.3. Map Validation using Historical Flood Events

Measuring the accuracy and validity of retrieved results is a crucial task in the risk assessment and susceptibility analysis of flooding (Ali et al., 2019). The validation of the final susceptibility map was evaluated by using data points from historical flood events in the study area. In Figure

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7, we collected 26 points from areas that were affected by flooding events, and then these points were compared to the susceptibility classes obtained using various flood biophysical influencing factors.

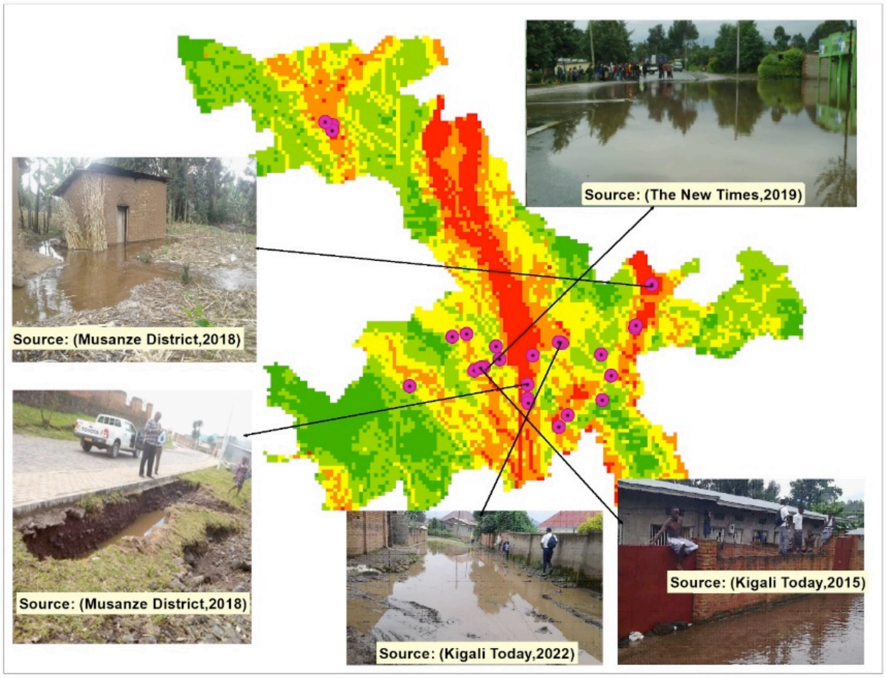

Figure 10: Flood susceptibility with historical flooding points (in peony pink color)

The majority of the sampled historical flooding points were found to be in high and very high susceptibility to flooding. In Figure 8, it was found that 18 points among 26 sampled are located in the area of high and very high susceptibility regarding the final flood susceptibility map. Therefore, since the majority of our points (24) were found to be in moderate, high and very high susceptibility to flooding we can conclude the validity of our final map in Figure 4.

3.4. Contribution to Future Policy Implications

According to reports, more than half of the world's population lives in cities, and urban flooding, as a result of extreme rainfall from climate change, is becoming a growing public concern (Hirwa et al., 2023; Tayyab et al., 2021). Thus, flood risk mapping will be useful in influencing future policies for assessing and mitigating flood impacts on cities. The Rwandan National Policy on Disaster Management's Strategic Plan of Action outlines three phases of disaster management: prevention/mitigation before disasters occur; disaster response; and disaster recovery (RoR, 2012). Therefore, geospatial analysis for flood risk assessment is one of the approaches that could be used to guide disaster management policy and anticipate flood hazards. With the advent of Earth observations, data availability has improved and extreme events are being monitored more closely (Hirwa et al., 2022). Besides, there is also the need to design and build a novel comprehensive national Information Systems (NIS) in the form of seasonal

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inventorying, monitoring and evaluation with full support of governments. The NIS would integrate remote sensing data, climate data, field survey data, weather forecasts at the national and local levels, as well as hydrological data, such as river flow information, into a central system.

4. Conclusion

Flood susceptibility mapping is one of risk reduction strategy that of pre-hazards management. Musanze city is considered a flood-prone area due to its proximity the main rivers. In this location, there are several evidences of destructive floods with some interval and return period. This research focused on flood susceptibility analysis using geospatial tool and decision-making strategy, such as the analytic hierarchy process (AHP). Many flood-inducing/conditioning factors that play a vital role in flood assessment were used. The selected conditioning factors were rainfall, land elevation, topographic wetness index, slope, land use land cover, clay content in soil, and distance from rivers. The multi-criteria and weighted overlay from this study has revealed that the area is classified in very low, low, medium, high and very high susceptibility to flooding. According to the final susceptibility map, Musanze City has 56 % of the total area under medium, high and very high vulnerable to flash floods. Residential area and settlements in Musanze City are the most exposed in high and very high risk to flooding. This demonstrates socioeconomic susceptibility in terms of severe property damage to facilities including roads, bridges, and other public and private settlements. It is suggested that the information gathered from this study be used to decision-makers in order to develop a better action plan and appropriate adaption techniques. For scientists, this study underscores the significance of incorporating historical flood events and various biophysical factors in flood susceptibility analysis. For urban planners, the results of this study can be used to design better drainage systems and to identify areas that require additional flood protection measures.

The study recommends increasing the drainage system in the city as a key solution to reducing floods. This is because the majority of flood events were found to occur in areas located amidst the main rivers passing through the city. This finding is consistent with previous studies, which have emphasized the critical role of drainage systems in preventing flooding in urban areas. Therefore, continual development and improvement of drainage systems are necessary to keep pace with the effects of extreme rainfall resulting from climate change.

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Data availability statement

All data used are publicly available and have been presented in this article.

Authorship Contribution Statement

All authors read, discussed the results at all stages, and refined the work. **Hubert Hirwa**: Conceptualization, Methodology, Software, Investigation, Acquisition of data, Formal analysis, Writing - original draft, review & editing. **Hyacinthe Ngwijabagabo:** Conceptualization, Methodology, Software, Investigation, Acquisition of data, Formal analysis, Writing - original draft, review & editing, **Marc Minani:** Writing – reviewing & editing**, Simon Pierre Cardinard Tuyishime:** Writing – reviewing & editing, **Innocent Habimana:** Writing – reviewing & editing.

Declarations of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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