

Urban Flood Susceptibility Study: An AHP-Based Geospatial Multi-Criteria Evaluation in Kigali City, with a Focus on the Mpazi Catchment

Pierre Damien Iraguha, Tresor Hirwa

¹Department of Spatial Planning, School of Architecture and Built Environment, College of Science and Technology, University of Rwanda, P.O. Box 3900, Kigali, Rwanda.
irpdamien@gmail.com.tresorhirwa099@gmail.com.

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Abstract

Surface water floods are the most common and costly natural calamities that affect all countries globally. Flooding in Mpazi catchment (MC) in the city of Kigali (CoK) has raised an issue to sustainable city development. The major aim of this study was to assess flood hazard, vulnerability, and risk in the part of Mpazi catchment (MC) by utilizing GIS-based Multi-Criteria Decision Analysis (MCDA). Mapping of flood hazard in Mpazi catchment was conducted by using twelve prominent parameters divided into two categories, one is flood hazard parameters (FHP) namely elevation, slope, drainage density, distance to the river, rainfall, soil and geology, while the others were flood vulnerability parameters (FVP) such as population density, land use and land cover, distance to road, global man-made impervious surface (GMIS), Human built-up area settlement extent (HBASE). Flood vulnerability parameters were used to generate a flood vulnerability map. Furthermore, flood susceptibility and flood vulnerability maps were generated and used to develop a flood risk map. The study on Mpazi catchment classified risk zones into very low, low, moderate, high, and very high flood risk zones. Southern areas with low elevation, slope, drainage density, and dense human-built structures were more vulnerable to flooding. The model's results aligned with historical flooding records.

Keywords: Mpazi catchment, flood susceptibility, Geo-spatial multi-criteria evaluation, AHP, City of Kigali

1. Introduction

Natural hazards, particularly flooding, have caused extensive damage globally, affecting both developed and developing nations. According to the World Bank (2019), over 62% of worldwide economic losses are attributed to natural hazards. In Rwanda, flooding alone results in substantial economic damage, with the country losing at least \$43 million annually. Recent projections indicate that Rwanda is expected to face annual losses of \$13 million from floods. Data from MINEMA (2010) show that between 2011 and 2019, Rwanda experienced 3,309 disasters, resulting in 254–134 deaths and the destruction of 5,691–15,910 houses. Floods are one of the most destructive natural disasters, particularly in Africa, where they pose significant challenges to both human livelihoods and economic sectors. Flooding disrupts communities, damages infrastructure, and negatively impacts the environment (Flooding in East Africa: The Impacts on and Implications for Cities in East Africa, n.d.). Key drivers of flooding include climate change, global warming, torrential rainfall, and overflowing streams, all of which result in severe property damage, socioeconomic losses, and fatalities (Hakizimana et al., 2021). As a result, experts are increasingly focused on flood identification, risk assessment, and management to mitigate these risks and minimize further socioeconomic losses.

Urban surface water floods, a type of pluvial flooding, occur when torrential rainfall overwhelms urban drainage systems, causing water to flood streets (Brouwer et al., 2007). These floods can rise more than 1 meter deep, leading to loss of life, destruction of infrastructure, contamination of water supplies, and the spread of waterborne diseases. In landlocked cities, heavy rainfall, deforestation, and urbanization exacerbate flooding (Knight et al., 2021), with impervious surfaces intensifying the impact of runoff. Flood prediction typically involves two approaches: (i) monitoring storm progression and (ii) assessing flood frequency. This enables the analysis of flood recurrence and its impact. Mpazi catchment, for instance, faces frequent flooding, particularly during the winter seasons, Itumba (February to May) and Umuhindo (September to December) both characterized by heavy rainfall. Flooding in Mpazi catchment affects the lower regions, including Nyabugogo Bus Park and the Nyabugogo River, causing widespread damage to infrastructure and posing a risk to public health due to increased waterborne diseases and pollution.

Mpazi catchment flooding has severe consequences, including fatalities and economic disruption. In 2019, six people were killed, two were severely injured, and 110 houses were destroyed. In subsequent years, floods claimed more lives and caused extensive damage to property. For instance, in 2022, seven people were killed, eight were injured, and 117 houses were destroyed in Nyarugenge District (MINEMA, 2022). Parts of the Mpazi flood ditch collapsed, highlighting the urgent need for effective flood management strategies. Despite efforts to reduce flood severity, the country aims to further minimize impacts in line with the Sendai Disaster Reduction Framework (SDRF) by 2030. Flood hazards in Mpazi catchment have been assessed using Geographic Information System (GIS) and Remote Sensing technologies. Multi-Criteria Decision Analysis (MCDA) has been employed to evaluate flood susceptibility and enhance decision-making. MCDA is particularly effective in assessing overlapping features and evaluating flood vulnerability (Akpan & Sylvester, 2022). Flood susceptibility refers to the likelihood of a specific area being affected by flooding and the degree of potential damage (Niyomugabo et al., 2022). Factors such as exposure to floodwaters, community resilience, and potential socioeconomic impacts are considered in these assessments (Brouwer et al., 2007).

Flood risk measurement quantifies the level of damage and loss due to flooding by considering various physioclimatic, hydrodynamic, economic, social, and ecological factors (Merz et al., 2009). However, the complexity of flood analysis is exacerbated by data inadequacy and inaccessibility. To address this, alternative methods such as numerical modeling and index-based analysis have been developed. The following sections will outline the methodology and data used in this study, present the results for flooding in Mpazi catchment, and provide a comprehensive discussion of the findings, followed by conclusions and recommendations.

2. Materials and Methods

2.1 Description of the Study Area

The Mpazi catchment is a thriving region in Kigali's Nyarugenge district that includes the Kimisagara, Nyakabanda, Rwezamenyo, and Gitega sectors. The watershed runs from the Nyamirambo sector's Rwezamenyo II cell to the Nyabugogo river, passing via seven cells: Nyakabanda II, Rwezamenyo, Kimisagara, Gitega, Kora, Akabahizi, and Nyabugogo. This area receives water from Mount Kigali and numerous man-made drainage systems. Mpazi catchment, which serves 8,035 families, receives the maximum water flow during the two main rainy seasons. Historical data reveal that the wettest months are April, November, and October, with rainfall averages of 347.88 mm, 367.58 mm, and 357.68 mm, respectively. The average temperature here is about 30°C (Kimani, 2020). The principal rainy seasons are February through June and October through December, with an average rainfall of 300 mm, which considerably contributes to floods (Niyomugabo et al., 2022). The Mpazi catchment covers 5.396 km² and is located at an elevation of 1,778 meters above sea level, between Nyarugenge hill and Mount Kigali. The surrounding topography influences the region's tropical wet climate, resulting in significant rainfall along Mount Kigali and increased flow into the basin. In recent years, notably in 2022 and 2021, the area has

seen catastrophic floods caused by extreme rainfall and urbanization, which exacerbates runoff and flooding.

Flood hazards in Mpazi catchment are assessed using Geographic Information Systems (GIS) and remote-sensing techniques. Researchers employ GIS overlay analysis, multi-criteria decision analysis (MCDA), and fuzzy methods to evaluate hazards and vulnerabilities. By combining geographic data with user expectations, these methods enhance decision-making (Akpan, 2022). The study relies on secondary data from sources like Meteorological Rwanda, MINEMA, REMA, and satellite imagery to provide comprehensive insights into the area's flood risks.

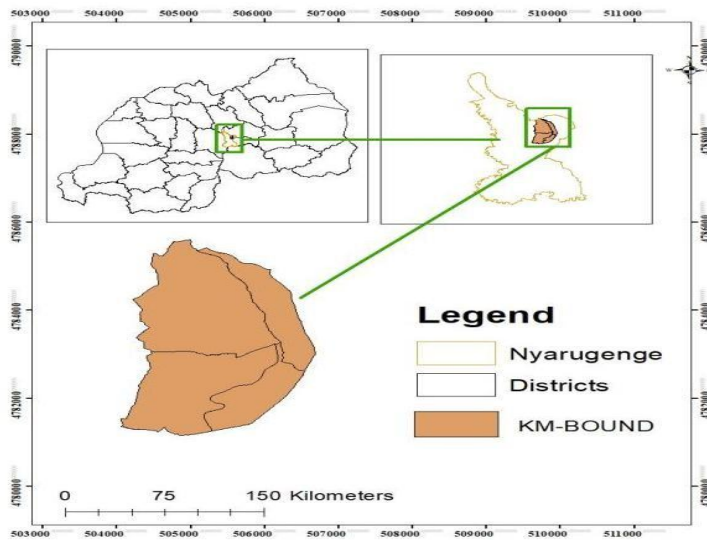


Fig. 1: Mpazi catchment location map

2.2 Flood Statistics Maps

The preparation of flood statistics maps is crucial for detailed assessment of flood susceptibility zonation. The flood susceptibility map of MC was made from FAO website, in historical flood events occurred during 2020-2022. The other maps incorporated to flood statistics map in MC, are, Flood points identified for deep analysis.

2.3 Gathering Data and Creating Thematic Map

Defining a clear and effective methodology is crucial for the quality of analysis study (Das, n.d.). Diverse input data are highly acquired to meet the objective of this research and to generate effective results (Berger et al., 2009). A secondary data acquisition approach was used as discussed before.

Table 1: Sources of Data.

SI Nc	Data type	source
1	Soil, Geology	www.usgs.com
2	DEM	www.usgs.com
3	LULC	www.usgs.com
4	Rainfall	www.livingatlas.com
5	Population density	www.nisr.org
6	GMIS	https://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1
7	HBASE	https://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1
8	Road Network (distance to road).	https://www.openstreetmap.org/export#map=9/25.4172/85.1660

2.4 Selection of the Thematic Layers for Flood Risk Zonation (FRZ)

Numerous multi-source spatial datasets are required to create a flood hazard vulnerability map for an area (Sculpher et al., n.d.). Some are highlighted (i) Map of geology, (ii) map of the soil (iii) DEM, (iv) Land use and land cover map (v) Population density map, (vi) GMIS and HBASE are two datasets. These datasets were used to create different themed maps in arc map. DEM was used to calculate relevant topographical and hydrological characteristics like drainage density, elevation, slope percentage and distance to the river.

2.4.1 Flood hazard Parameters (FHP)

Flooding hazard parameters (FHP) such as rainfall, topography, drainage system, geology, soil nature and other physical features, are used to determine the extent of flooding (Das, 2023). During our research that we conducted through literature review, we only considered seven FHPs that enhance flooding.

2.4.1.1 Elevation

Normally during raining period, water moves from high elevated area towards lowlands, this makes low elevated areas to be more susceptible to flooding. In MC, we used DEM to assess the topographic characteristics. Elevation of MC ranges from 1361-1716 MSL, high elevated regions are found in the upstream of the study areas specifically Nyakabanda II and the parts of Kimisagara that lies on mount Kigali escarpment, this triggers considerable runoff after heavy rains, causing dangerous flooding downstream.

The effects of flood were classified into various levels regarding their severity towards socioeconomic deterioration. The areas with very high elevation ranging from 1361m to 1716m were classified as having very low flood effect. Areas with 1619m to 1716m were classified as having low impact. Areas with elevation between 1462m and 1938m were classified as having high impact and the areas with 1538m to 1619m were concerned to have moderate flooding impact While the areas with 1716m to 1848m were classified as having very low flooding impacts, the figure A below shows.

2.4.1.2 Slope

Slope is also a prominent parameter that triggers flooding. Its direct impacts are obvious through increasing the runoff accessibility, volume and velocity of water, surface runoffs and groundwater infiltration. The classification of slope in percentages was ranged as follows; very high (0-8.06), high class (8.03-13.79) moderate (13.79-20.79), low class (20.79.-30.45), very low (30.47-52.5), as the figure B below shows.

2.4.1.3 Drainage Density

Drainage density is among the prominent parameters that lead to floods. When the drainage density is high, also the runoff is critical and enhances the chance of flooding. Many approaches have been used to determine drainage density for Mpazi drainage system and it was estimated to be 1663.7 which reflects that the basin is more prone to flooding. In this research, the drainage density map was classified into five classes. The very high hazard (857.891663.7), the high hazard class (569.021-85.8), the moderate hazard class (360.1-565.0), the low hazard class (126.1-360.1) and the very low hazard (0-126.5), as the figure C depicts.

2.4.1.4. Distance to the Drainage

The distance to the drainage is crucial in determining the flood risk zones and the flood hazard index (Osman & Das, 2023). Areas that are located near water streams are more susceptible to flooding while the parameter's weight reduces as the area is located far from the drainage (Khosravi et al., 2019). The theme map in ArcMap was divided into five categories namely; extremely high (0-0.000739), high (0.000739-0.000155), moderate (0.000155-0.000246), low (0.000246-0.000362) and very low (0.000362-0.00628), as the figure D below show.

2.4.1.5. Rainfall

The rainfall parameter is critical in this comprehensive flood susceptibility study in Mpazi drainage system. The Inverse Distance Weighted (IDW) approach has been utilized to depict spatial distribution of rainfall.

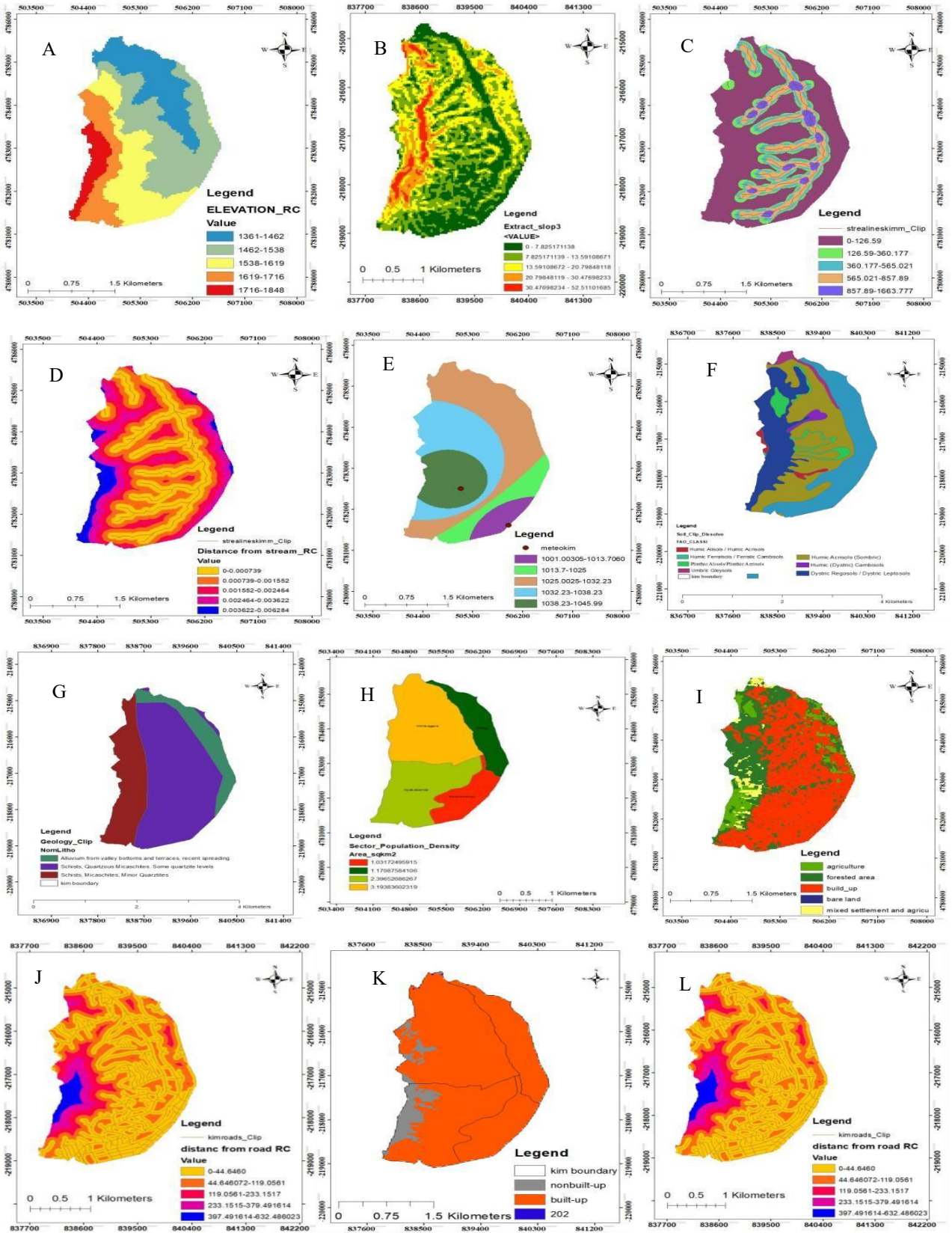
Heavy rainfall leads to heavy flooding while low rainfall depth leads to low flooding. The rainfall was scaled as follows; very high (1038-1045), high scaled (1031-1038), moderate (1025-1032), low class (1013-1025) and very low scaled (1001-1013), the figure E below shows.

2.4.1.6. Soil types

Morphological and physical characteristics of soil help to describe its contribution to flood occurrence. Increase of infiltration reflects high level of its permeability which in turn reduces the chance of flooding(Archer et al., 2020), while the impermeable layers of soil such as rocks enhances surface runoff(Ogden et al., 2011), hence increase flood susceptibility within the study area(Horton, 2021.). The degree of soil porosity determines its degree of permeability, more porous formation reflects high permeability and reduces flood risk and vice-versa, figure F below depicts.

2.4.1.7 Geology

Normally, the geology of an area can affects flood occurrence(Khosravi et al., 2019). This aspect contributes considerably to the amplification of floods. Local geology keeps track of paleo-flood occurrences that can be used to estimate the frequency of recent water floods. Rainwater infiltration is facilitated by soil porosity characteristic(Ogden et al., 2011). This reduces flood risk whereas impermeable soil layers like clay, gypsum, etc. On the other hand, increase of runoff rates, increase flood (limestone and marly), moderate (alluvium, silty sediments and Quaternary sediments), low flood hazard category (sandy clay, sands and conglomerates), very low flood hazard class (coarse sand), (Osman, S. A., & Das, J. ,2023).Figure G below depicts.



2.4.2. Flood Vulnerability Parameters (FVP)

2.4.2.1 Population Density

Flood vulnerability is directly linked to population density since more people creates more infrastructures that tremendously reduce infiltration and reflects that more people are exposed to horrible events (Waqas et al., 2021). As the figure H shows above, the five categories of population density in MC on the arc map 10.8.1 thematic map is: high (Kimisagara) moderate (Nyakabanda), low (Gitega) and very low (Rwezamenyo).

2.4.2.2 Land Use and Land Cover

One of the most prominent factors for flood occurrence is land use and land cover. Areas with high density of vegetation are less vulnerable to flood since they slow rapid water flow and enhance infiltration (Liu et al., 2014). In urban areas like Kigali, runoff increases due to impermeable surfaces and little infiltration (Allafta et al., 2021). Allafta and Opp (2021) described shrub land, cropland, bare land, urban and water body as very low, low, moderate, high and very susceptible to flooding, respectively. Das and Gupta considered water body, built up area, agriculture, sparse vegetation and dense vegetation as very high, high, moderate, low and very low susceptible to flooding. Likewise, the land use map of MC was categorized as very high (built up area and water body), high (bare land), moderate (grassland), low (shrubs) and very low (dense vegetation) vulnerable to flooding. Built up area of the study area is the most vulnerable category to flooding, the figure L above shows.

2.4.2.3 Distance to the Roads

Distance from the roads also is the other crucial factor for assessing flood prone in an area since roads restrict water entry into the earth's surface and slows down infiltration process (Pregolato et al., 2017). As a result, spaces with more road networks are mostly destroyed by intense rainfall, hence flooding. In addition to that, due to reduced infiltration and speedier runoff, neighboring areas of the roads are more susceptible to flooding. In this research on MC, they were ranked as follows: Very high (0-41.6), high (44.6-119.0), moderate (119.0-233.1) low (233.1-379.4) and very low (379.4-632.4) susceptible to flooding, the figure J above illustrates.

2.4.2.4 GMIS (Global Man-Made Impervious Surface)

Asphalt, sand, stone, concrete, bricks, glass and other man-made materials are used to create water repellent surfaces that prevent water from penetrating the soil (Negese et al., 2022). Flooding gets more accelerated when impervious surfaces enable more water to flow as surface or sub-surface runoffs. As the figure K above proves, we scaled very high (0-19), high scaled (19-46), moderate scaled (46-73) and low scaled (73-100), very low (100-200).

2.4.2.5 HBASE (Human Built-Up Area Settlement)

Encroachment of urban areas to natural and grass land areas hinders their capabilities to act as natural flood retention zones, this is proven through increased built-up areas and infrastructures at large (Firehock & Walker, 2015). This causes a considerable effect in terms of flood water management in urban areas. Figure L above illustrates, we ranked this into two categories namely very high scaled (built up), low scaled (non built up).

2.5.1 Analytical Hierarchy Process

Analytical Hierarchy process uses hierarchical structures to present a problem and prioritize alternatives basing on judgement of the user (Saaty, 1980.) and is based on paired comparisons. The weight and evaluation of criteria must be determined according to their importance. AHP consists of six steps (Saaty, 1980.) namely; breaking a complex unstructured problem down into its component factors, developing AHP hierarchy, paired comparison matrix determined by imposing judgement, assigning values to the subjective judgement and calculating the relative weights of each criterion, synthesize judgement to determine priority variables and check consistency of assessments and judgments. The main point of AHP

is calculating consistency ratio (Saaty,1980.). The mentioned matrix can be considered as an acceptable one, when it is less than 0.1. Using twelve flood susceptibility factors, flood maps were generated. Therefore, using saaty scale 1980 that ranges from 1-9 each factor was weighted according to its contribution.

2.5.2 Consistency Index (CI)

It is common practice to verify that results are consistent by applying the transitivity criteria. The value of λ_{max} is computed using the formula below:

$$\lambda_{m} = \frac{1}{n} \sum_{j=1}^n \lambda_{j}$$

The researcher does a consistency check for this kind of dilemma to see whether the comparison judgment is sufficiently consistent or whether the exercise needs to be repeated before moving further. As to Saaty's (2006) findings, the matrix's consistency ratio is regarded as 5% is about right. The outcomes showed that the CR was around 5.5%, indicating that the matrix's prioritizing was accurate in terms of the factor-assigned expert judgment score. The AHP priority calculator was used to perform procedures and computations.

2.5.3 AHP Flood map

Flood risk is the result of having both flood hazards and vulnerabilities at a particular place (Kron,2005). Systematic variable assessment, collection, and analysis are thus necessary. GIS is now a crucial tool for flood mapping and research since it makes it possible to create maps of flooded areas(Liu et al., 2014).

Risk = Hazard index × Vulnerability index

The significance and contribution of each theme indicator class and layer to the hazard and susceptibility were considered once the study weighed them. To identify and zone flood risk regions, the overlay technique was applied to the variables to assess risk and vulnerability first, followed by a cross-hazard and vulnerability analysis. Every action in ArcGIS was completed using the raster calculator included in the spatial analyst tools. Using the natural break approach, the prepared flood hazard, vulnerability, and risk maps have been divided into five classes: very low, low, medium, high, and very high.

3. Results

3.1 Analyzing of Flood Influencing Factors for Creating Flood Hazard Mapping

The final flood susceptibility map Mpazi drainage system was generated by integrating twelve flood susceptibility factors. The weighted overlay integration ranked into five classes' namely; very high (5), high (4), moderate (3), low (2), and very low (1) susceptibility. While the flood hazard map was generated using seven flood hazard parameters (elevation (E), slope (SL), drainage density (DD), distance to river (DR), and yearly rainfall (R), geology (G), soil (S). In order to compare these components and sub factors, a comparison matrix table was created for the study. display the flood hazard thematic layers' normalized vector. In this regard, we also established a random index among the components and sub factors.

After that, the CR value was determined, and the resultant CR value was 0.6 follows logically that such elements and sub-elements can be taken into consideration in AHP analysis. demonstrates the relative weight given to each element and all its sub-elements in the research. Thus, elevation may be the most important element in identifying locations that are likely to produce flood. The next most significant factors that significantly influence the identification of areas that are likely to produce flood are drainage density, slope, and river vicinity. On the other hand, it was discovered that the study's least impacted elements were soil, geology and rainfall. When it came to creating the dietary susceptibility map for the research area, none of these criteria are really relevant.

The raster format was reclassified using the spatial analyst tool (SAT) according to the level of flooding. Each parameter rate was allocated to a distinct flood hazard category, and these components were reclassified into five danger categories (very low hazard level, low flood hazard, moderate flood hazard,

high flood hazard, and very high flood hazard) based on the amount of flood hazard. The degree of flood producing factors that create floods is determined by a combination of professional competence, personal judgment, local knowledge, and data from previous research. In comparison to sloping areas where runoff flows farther downhill, flooding happens more quickly in flat areas. One of the parameters is the terrain's slope, which is the most commonly used and wellknown topographic size element.

3.2 Flood hazard mapping

Like prior flood hazard research, this study integrated the seven flood-affected strata to create a flood hazard map. Moreover, some studies only have four or six components. In general, nevertheless, it is advised to include more than six components to reduce the possibility of overrating particular characteristics because of non-representative ratings influenced by a single element. The literature claims that there is no standard method for automatically determining class boundaries; instead, the majority of research relies on their own subject-matter knowledge and experience.

Many experts believe that locations that are prone to flooding have a combination of low elevation, low slope, and high drainage density. The danger was categorized into five primary groups using the natural breaking slope technique in the "ArcGIS 10.8.1 environment": very high, high, moderate, low, and very low hazard zones. Using secondary data and the AHP reclassification approach for seven sub-criteria, flood danger maps were produced. The areas designated as very high and high flood hazards, areas classed as medium flood hazards, and regions classified as low and very low flood hazards were all present in the final flood hazard map created using the AHPGIS approach.

3.2.1 Weighted Sum

To rank one factor's relative worth to another, weighting procedures are applied. In a weighted overlay, a component's importance relative to the other components increases with its weight. The seven floods and corresponding coefficients for Mpazi drainage system described before were superimposed to generate the final flood hazard map.

3.3 Analyzing of Flood Influencing Factors for Creating Flood Vulnerability Mapping

The five key flood contributing parameters population density (PD), land use and landcover (LULC), distance to road (DR), global man-made impervious surface (GMIS), and human built-up and settlement extent (HBASE) were used to create the flood vulnerability map. To compare these components and sub-factors, a comparison matrix was created specifically for this study. After that, the eigenvector was computed and normalized. In this regard, we also computed the random index among the factor and sub-factors. The CR value was then computed, and the resulting CR value was 0.6 as a result, it is plausible to conclude that such components and sub-factors can be included for AHP analysis. The study's relative relevance of each element and its sub-factors is reflected in. As a result, human density may be the most essential factor in designating flood-prone areas. Following population density, the next most important criteria that impact flood sensitive regions are land use, land cover, distance to road, GMIS and HBASE, on the other hand, was shown to be the least impacted aspect in the research.

The flood vulnerability map was created by combining thematic layers such as population density, land use/land cover, road distance, GMIS, and HBASE. The components that impact flood-prone regions, as well as their weightings, are allocated using expert judgment and past case studies. Based on the cumulative vulnerability score, flood vulnerability is classified into four categories: very low, low, moderate, high, and very high. For five subcriteria, the flood vulnerability maps were constructed using secondary data and the AHP reclassification approach. The final flood vulnerability map produced by the AHP-GIS approach revealed that the locations classified as very high and high flood susceptible, as medium flood vulnerable, and as low and extremely low flood vulnerable. The table below depicts the results.

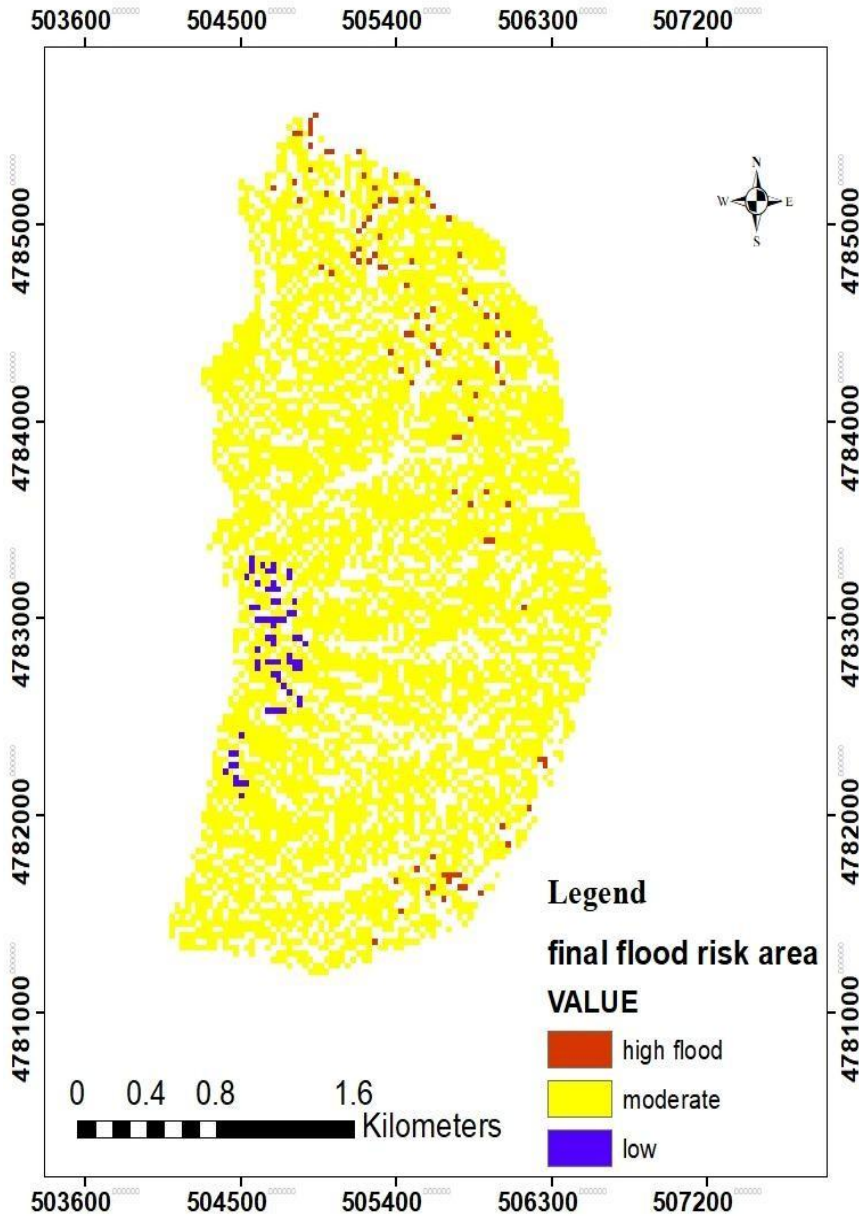


Fig 1: Flood mapping of MC a Flood Inventory map b Flood hazard mapping using AHP of MC Flood Vulnerability mapping and d Flood risk mapping.

Table 2: FVP and FSP results

CRITERIA	CLASSVALUE	CLASS RANGE	VURNERABILITYLEVEL
TWI	-8.332_-6.047	1	very low
	-6.047_-4.73	2	low
	-4.73_-2.94	3	moderate
	-2.94_-0.082	4	high
	-0.082_7.57	5	very high

Elevation	1361-1462	1	Very high
	1462-1538	2	high
	1538-1619	3	moderate
	1619-1716	4	low
	1716-1848	5	very low
slope	0-8.03	1	Very high
	8.03-13.79	2	high
	13.79-20.79	3	moderate
	20.79-30.45	4	low
	30.45-52.5	5	very low
precipitation	1001.003-1013.706	1	very high
	1013.7-1025	2	high
	1025.00-1032.23	3	moderate
	1032.23-1038.23	4	low
	1038.23-1045.99	5	very low
LULC	0	1	high
	0-2	2	moderate
	2_3	3	very high
	3_5	4	low
	5_6	5	very low
NDVI	0.018107-0.10238	1	very high
	0.10238-0.159135	2	high
	0.159135-0.22277	3	moderate
	0.22277-0.301883	4	low
	0.301883-0.456669	5	very low
Distance from the streams	0-0.000739	1	very high
	0.000739-0.001552	2	high
	0.001552-0.002464	3	moderate
	0.002464-0.003622	4	low
	0.003622-0.006284	5	very low
distance from road	0-44.6460	1	very high
	44.64-119.05	2	high
	119.056-233.151	3	moderate
	233.151-379.491	4	low
	397.491-632.486	5	very low
drainage density	0-126.59	1	very low

	126.59-360.177	2	low
	360.177-565.021	3	moderate
	565.021-857.89	4	high
	857.89-1663.777	5	very high

3.3.1 Weighted Coefficients

The flood producing characteristics used in this study were estimated using the Analytical Hierarchy approach (AHP) in pairs to establish flood vulnerability priority. A pairwise comparison of one element to another is conducted after repeating iteration until the required consistency ratio is smaller than 1 or 0. The decision matrix, which is based on the main eigenvector, provides the outcome weight.

3.4 Flood Vulnerability Mapping

In this study, the five flood affecting layers were used to generate a flood vulnerability map. Based on the natural breaking technique, the resulting vulnerability was split into four groups in the "ArcGIS 10.8.1 environment": very high, high, moderate, low, and very low susceptible zones. For five sub-criteria, flood vulnerability maps were generated utilizing secondary data and the AHP reclassification approach. The AHP-GIS approach generated a final flood vulnerability map that included FVP and FSP of the site categorized as very high and high flood hazard, as medium flood hazard, low and very low flood danger, respectively. The table 3 above depicts.

3.4.1 Weighted Sum

To rank one factor's relative worth to another, weighting procedures are applied. In a weighted overlay, a component's importance relative to the other components is indicated by its larger weight. The above flood vulnerability map was overlaid to generate the final version. Five floods for which the Mpazi drainage system has coefficients associated with them.

3.5 Flood Risk Mapping

The flood hazard zone (FHZ) and flood vulnerability zone (FVZ) maps are combined to create the flood risk zonation (FRZ) map, which is the study's ultimate output. Five Danger categories, from extremely low to very high, are shown on a map to illustrate the likelihood of flooding. The areas classified as very high and high flood risk, the areas classified as medium flood risk, and the regions classified as low and very low flood risk were included in the final flood risk map produced using the AHPGIS approach. The majority of the coastal regions, particularly those in the Nyakabanda II, Gitega, and Kimisagara cells, are at high and extremely high danger of flooding.

3.6 Validation of the Module

The AHP result was statistically validated using the flood inventory map using ROC-AUC. The ROC-AUC was calculated by comparing the FHZ map to 50 flood locations using the ArcGIS software's 'ArcSDM' tool. Figure 13 depicts the AHP model's ROC curves and AUC. As a result, according to the satisfaction scale, the model efficiently produces the FHZ map, which is regarded as an excellent conclusion.

4. Discussion

The current study employs a GIS-based Analytical Hierarchy Process (AHP) approach to estimate flood risk in the lower section of the Mpazi drainage system. The primary objective was to identify flood-prone areas by analyzing seven key flood-influencing factors: elevation, soil, drainage density, slope, geology, river distance, and annual rainfall. By applying pairwise comparisons through AHP, weighted coefficients were assigned to prioritize these flood risk factors. The flood hazard map was developed by integrating the seven flood-influencing parameters using the AHP-GIS approach, while the flood vulnerability map was

created by combining five critical variables: population density, land use and land cover (LU&LC), distance to roads, GMIS, and HBASE. These maps were then used to create a flood risk map, with the natural breaking technique categorizing areas into five classes: very high, high, moderate, low, and very low flood risk. The final results revealed that elevation, slope, drainage density, and proximity to rivers were the most influential factors in determining flood-prone areas. In contrast, soil type and geology were found to have the least impact. According to Muchiri, although the Mpazi basin receives relatively low rainfall (100–600 mm annually), surface runoff is directed through the basin, causing frequent flooding as neighboring cells along the path of maximum descent accumulate water. The study also noted that the Mpazi drainage system has been historically affected by destructive floods, which have damaged infrastructure and led to fatalities.

The importance of this study aligns with the Sendai Framework for Disaster Risk Reduction (SFDRR), which emphasizes the need for improved risk understanding, better disaster preparedness, and enhanced resilience. In accordance with SFDRR's goal of reducing disaster risk by 2030, this study addresses the necessity of prioritizing vulnerable populations such as children, the elderly, people with disabilities, and low-income households when assessing flood impacts. The findings also highlight the importance of early warning systems and catastrophe risk reduction through spatial flood risk assessments. By incorporating Multi-Criteria Decision Analysis (MCDA) in flood risk mapping, the study accounts for diverse stakeholder perspectives and parameter weights, offering a holistic approach to flood risk analysis. This method helps address the complexity of flood risk, which encompasses social, environmental, physical, and economic dimensions. The resulting maps can serve as crucial tools for local governments and decision-makers to enhance land-use planning, disaster preparedness, and flood risk management, particularly in the context of climate change. The study further demonstrates the value of high-resolution satellite imagery in refining flood risk assessments for areas classified as high and very high risk. The use of multisource geospatial data enhances the accuracy and reliability of natural disaster analysis, making the case for continued adoption of geoinformatics in disaster risk reduction efforts. Additionally, the integration of hazard and vulnerability layers allows for a more comprehensive understanding of flood risk, facilitating proactive decision-making and mitigation measures.

In summary, this study offers practical insights for improving flood risk management in the Mpazi drainage system and beyond. By utilizing GIS-based AHP and MCDA methodologies, it provides decision-makers with critical information for reducing flood-related risks, building resilience, and safeguarding lives and property. Moreover, the study's approach aligns with the broader objectives of the Sendai Framework, which aims to enhance disaster preparedness and promote sustainable development by minimizing the risks posed by natural hazards.

5. Conclusion

This study aimed to apply a GIS-based AHP approach to analyze flood-triggering factors and create flood hazard, vulnerability, and risk maps for a section of Kigali's Mpazi drainage system. By integrating key parameters such as elevation, slope, rainfall, drainage density, population density, and land use, the study produced a comprehensive flood risk map. The findings highlight high-risk zones and provide critical insights for decisionmakers to guide preventive actions, improve land-use planning, and enhance flood risk management, especially in the context of climate change. The practical implications of this study are significant for addressing Africa's socio-economic development challenges. The use of geospatial techniques and multi-criteria analysis supports innovative approaches to natural disaster management, which are vital for sustainable development. High-resolution satellite imagery and further mapping are recommended for refining the data, underscoring the importance of research and innovation in mitigating disaster risks and promoting resilience across vulnerable regions in Africa.

6. References

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