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Spatial Analysis of Flood Hazard for the Risk Reduction in Rwanda

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Abstract

Mapping of flood hazard reveals its occurrence likelihood and increases the preparedness and adaptation among the community. This study aimed to spatially analyze flood hazard towards its risk reduction in Kamonyi district, southern Rwanda. The study used secondary data on flood events (deaths and injuries, destroyed houses and damaged croplands, road and electrical lines damaged and lost livestock) collected from the Rwanda's Ministry in Charge of Emergency Management (MINEMA) from January 2013 to April 2020. These recent flood events, literature review and experts opinions helped to select ten flood triggering factors namely elevation, slope, rainfall, land use and land cover (LULC), Normalized Difference Vegetation Index (NDVI), Topographic Wetness Index (TWI), distance from roads, distance from rivers, lithology and soil texture. These factors were merged together to produce flood hazard map through the Fuzzy Overlay method of the Spatial Analyst Tools in the Geographic Information System (GIS). The analysis highlighted elevation, slope and rainfall as major factors and flood mapping marked the Rukoma, Gacurabwenge, Musambira, Nyarubaka and Kayumbu sectors as highly prone to flood. For the prediction of flood occurrence from 2020 to 2050, the authors used Microsoft Excel and referred to recent flood cases. The results showed that Karama and Rugarika sectors are likely exposed to future occurrence. For the flood risk reduction, policy makers are suggested to consider each sector since the experience on flood differs by sector and rainwater harvesting along with development of terraces would help to minimize the runoff from which results flooding. This flood hazard mapping can help decision-makers, economic operators and other occupants to determine the areas that may potentially be impacted while the prediction of flood future occurrence will help the decision makers in better planning as well.

Keywords

Flood, Geographic Information System, Hazard, Kamonyi District, Risk Reduction, Rwanda

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1. Introduction

Floods are the most common natural hazards that affect societies around the world, affecting 80% percent of the world's population. It is estimated that more than one third of the world's land area is flood-prone [1, 2]. In Rwanda, due to its dense river network and large wetlands, the country is threatened mainly by riverine floods, and the agriculture sector is the most affected by flood hazards [3, 4]. According to the report of Rwanda's Ministry in Charge of Emergency Management [5], between 2016 and 2019, floods caused 65 deaths, 11 injured, 2548 houses damaged, 5,917 ha of croplands damaged. Also, one health center, 5 water line, 44 bridges, 5 water lines and 5 roads were damaged.

Despite the fact that flood has been reported to frequently occur in Kigali city and some parts of Northern Rwanda, the southern Rwanda also faces its occurrence [6]. For example, between 2011 and 2019, flooding in Kamonyi district of the

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southern Rwanda led to 18 deaths, 12 injured, 2873 houses damaged, 804.5 ha of croplands damaged, 125 livestock lost, 4 classrooms destroyed. In addition, one administrative building was destroyed, 12 bridges and 11 roads were damaged [5]. Those losses and damages caused by flood can explain how the district is prone to its occurrence, and explain that a research on flood hazard mapping is of paramount importance in this area.

The study of [7] mapped flood susceptibility and its risk perception in Rwanda. However, the study considered the entire Rwandan territory and some factors were omitted like lithology and soil texture. The recent studies on flood hazard analysis conducted in Kigali city has merely based on community perception and recent event consideration. These studies [8-10] did not indicate the major factors causing flood in Kigali city apart from highlighting that the recorded losses resulted from intense rainfall. Furthermore, the study of [11] conducted a study on disaster risk reduction in Kamonyi. Their study only used questionnaire and interview to assess the community perception and attitudes toward disaster risk reduction and omitted the analysis of disaster causal factors.

Although the above studies tried to map flood susceptibility, hazard and vulnerability, no similar studies have considered Kamonyi district which is listed among areas under flood threat [3]. The authors recognized this gap and chose to undertake this research by considering Kamonyi district in order to map its flood hazard, indicate its major occurrence drivers as well as future occurrence likelihood based on recent events. This mapping of flood hazard will serve policy makers, decision makers and planners to ensure relevant planning and implementing flood hazard mitigation measures for the sustainability of the community and environment as well.

2. Methods and Materials

2.1. Description of Study Area

This study considered Kamonyi district of the southern province of Rwanda. The district is composed by 12 sectors: Gacurabwenge, Karama, Kayenzi, Kayumbu, Mugina, Musambira, Ngamba, Nyamiyaga, Nyarubaka, Rugarika, Rukoma and Runda as illustrated in the Figure 1.

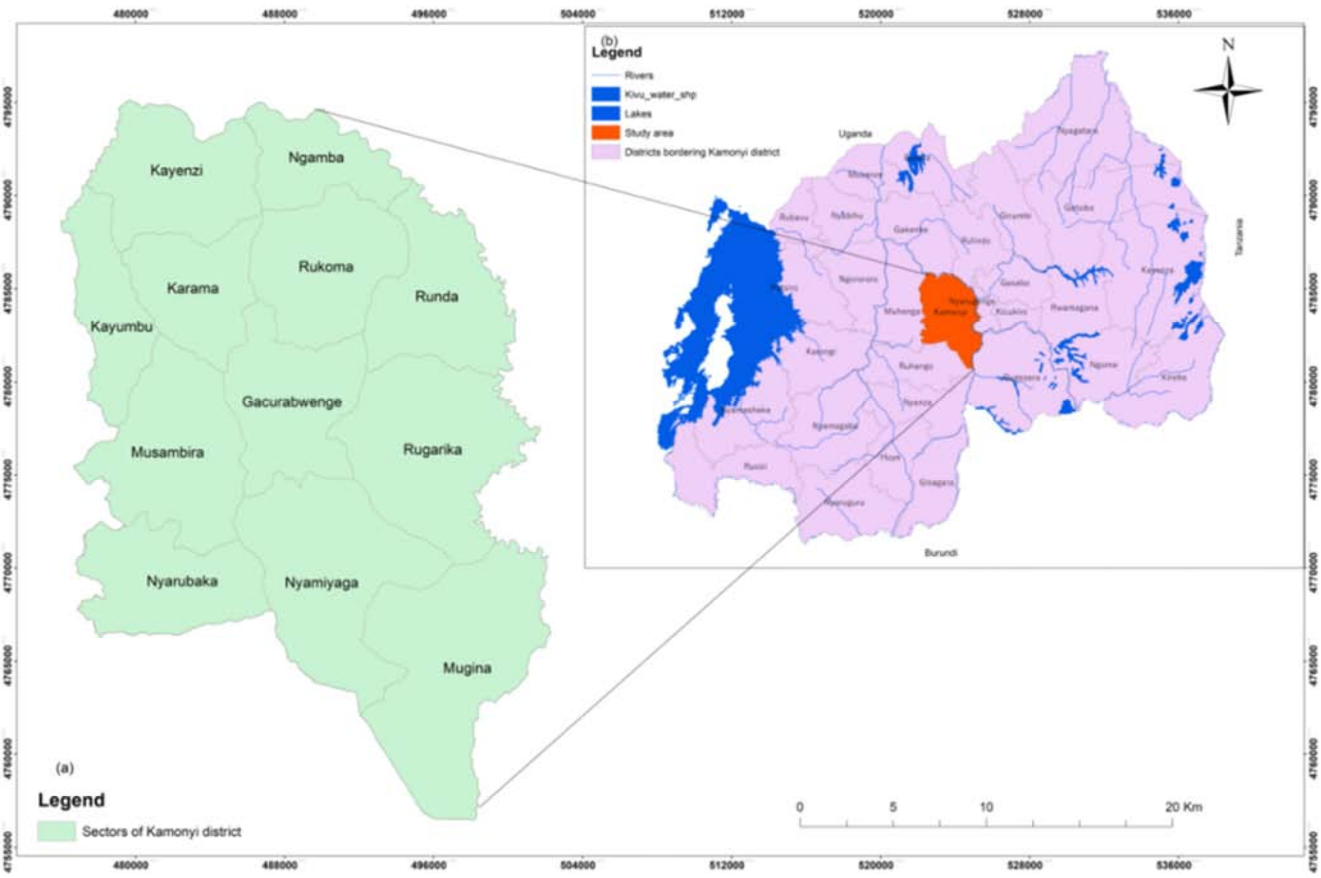

Figure 1. Map indicating the (a) sectors of Kamonyi district and (b) its bordering districts of Rwanda.

The district is populated by 377,257 inhabitants from 85,285 households on a total surface area of 655.5 km² [12]. The district of Kamonyi shares its borders with Ruhango District in the South, Muhanga District in the West, Bugesera and Nyarugenge Districts in the East.

2.2. Datasets Types and Sources

2.2.1. Flood Triggering Factors

For this study, ten factors which cause flood hazard were employed and their selection was mainly based on the literature review, field reality and experts' knowledge on flood hazard mapping. The choice of these factors was based on recent studies on flood in Rwanda [4, 8, 13]. The authors also considered the national disaster risk management policy, and contingency plan for flood and landslide in Rwanda [3] as expert opinion. The flood causal factors considered by this study were elevation, slope, rainfall, land use and land cover (LULC), Normalized Difference Vegetation Index (NDVI), Topographic Wetness Index (PWI), lithology, soil texture, distance to roads and distance to drainage. The Geographic Information System (GIS) and Remote Sensing tools were employed to process and map the above flood causal factors.

The elevation and slope angles employed by this study were derived from Digital Elevation Model (DEM) of 30 m resolution. These datasets were acquired from the United States Geological Survey Earth Explorer [14]. Five elevation classes obtained were: 1,330 - 1,437 m, 1,437 - 1,537 m, 1,537 - 1,629 m, 1,629 - 1,728 m and 1,728 - 1,973 m. And the classified slope in angles throughout Kamonyi district ranged from 0-50, 5-100, 10-150, and 15-230 to 23-590. The rainfall monthly precipitation data were interpolated by using 19 years (2000-2019) rainfall data collected from meteorological stations operating across the study area. These data were provided by the Rwanda Meteorology Agency [15]. The study employed monthly rainfall due to the reason that hourly or daily rainfall could not be available since some years had incomplete datasets. Thus, it was preferred to employ monthly data which were complete from 2000 to 2019. The classified mean monthly rainfall was ordered as: 41.8 - 45.6 mm, 45.6 - 48.9 mm, 48.9 - 52.4 mm, 52.4 – 56.1 mm and 56.1 – 60.8 mm, respectively.

In addition, the authors recognized the fact that the type of the land coverage represents the likelihood of the land exposure to erosion and other runoff risks including flooding. For this study, land use and land cover (LULC) map of 2020 was produced from multispectral Landsat-8 Operational Land Imager (OLI) images. These images were acquired from the United States Geological Survey Earth Explorer [14]. The land cover/use map was classified and five LULC classes (forestland, grassland, cropland, built-up areas, wetland and water bodies) based on the East African Classification of Regional Center for Mapping and Resources Development [15, 16].

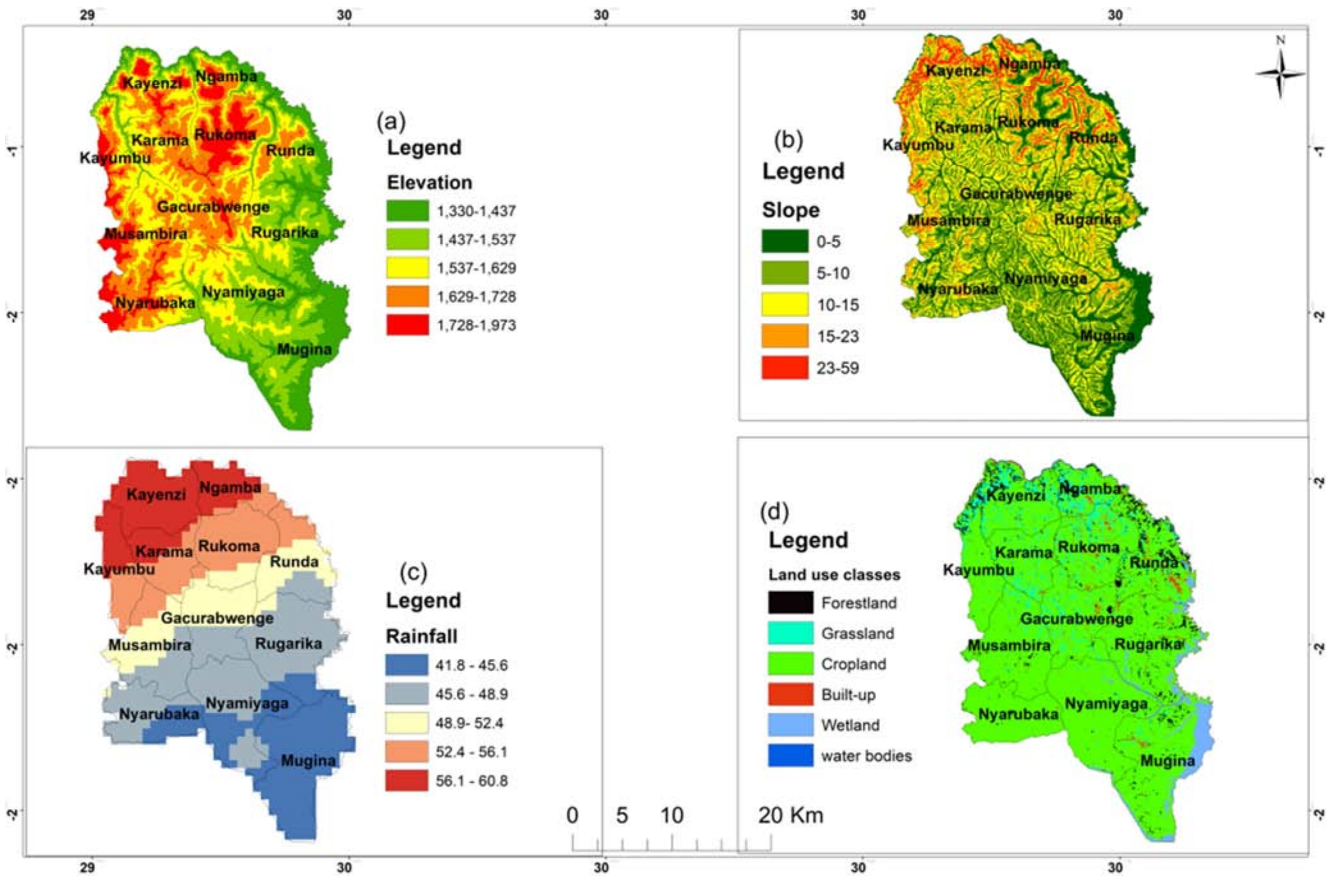

Figure 2. Flood triggering factors (a) elevation, (b) slope, (c) rainfall and (d) land use and land cover.

The authors also employed the distance to roads and distance from rivers and/or drainage expressed in meters. The shapefiles of both rivers and roads of the study area were acquired from an online database (http://www.diva-gis.org/gdata). Both distance to rivers and distance to roads were produced by creating Euclidean distance in ArcMap-Spatial Analyst extension. The distance to roads was: 0-250 m, 250-500 m, 500-750 m, 750-1,000 m and 1,000-1,250 m while the distance to rivers was: 0 - 500 m, 500 - 1,000 m, 1,000 - 1,500 m, 1,500 - 2,000 m and 2,000 - 2,500 m. The obtained Topographic Wetness Index (TWI) for Kamonyi district (Figure 3c) showed a highest value ranging between 13.1 and 23.4 while the obtained lowest TWI was from 2.2 to 4.7. Regarding the NDVI, as indicated in Figure 3d, the classified Normalized Vegetation Index (NDVI) revealed five classes. The lowest class scored from 0.77 to 0.83 and the highest became 0.31 to 0.57.

The authors recognized the fact that the Normalized Difference Vegetation index (NDVI) indicates a quantitative estimate on the vegetation density [17]. The NDVI used by this study was acquired from the Moderate Resolution Imaging Spectroradiometer (MODIS, 250M resolution) downloaded from an online database (ladsweb.nasacom.nasa.gov/data/html).

$$\text{NDVI} = \frac{IR-R}{IR+R} \quad (1)$$

Where IR is the infrared portion of electromagnetic spectrum and R value is the red portion of electromagnetic spectrum.

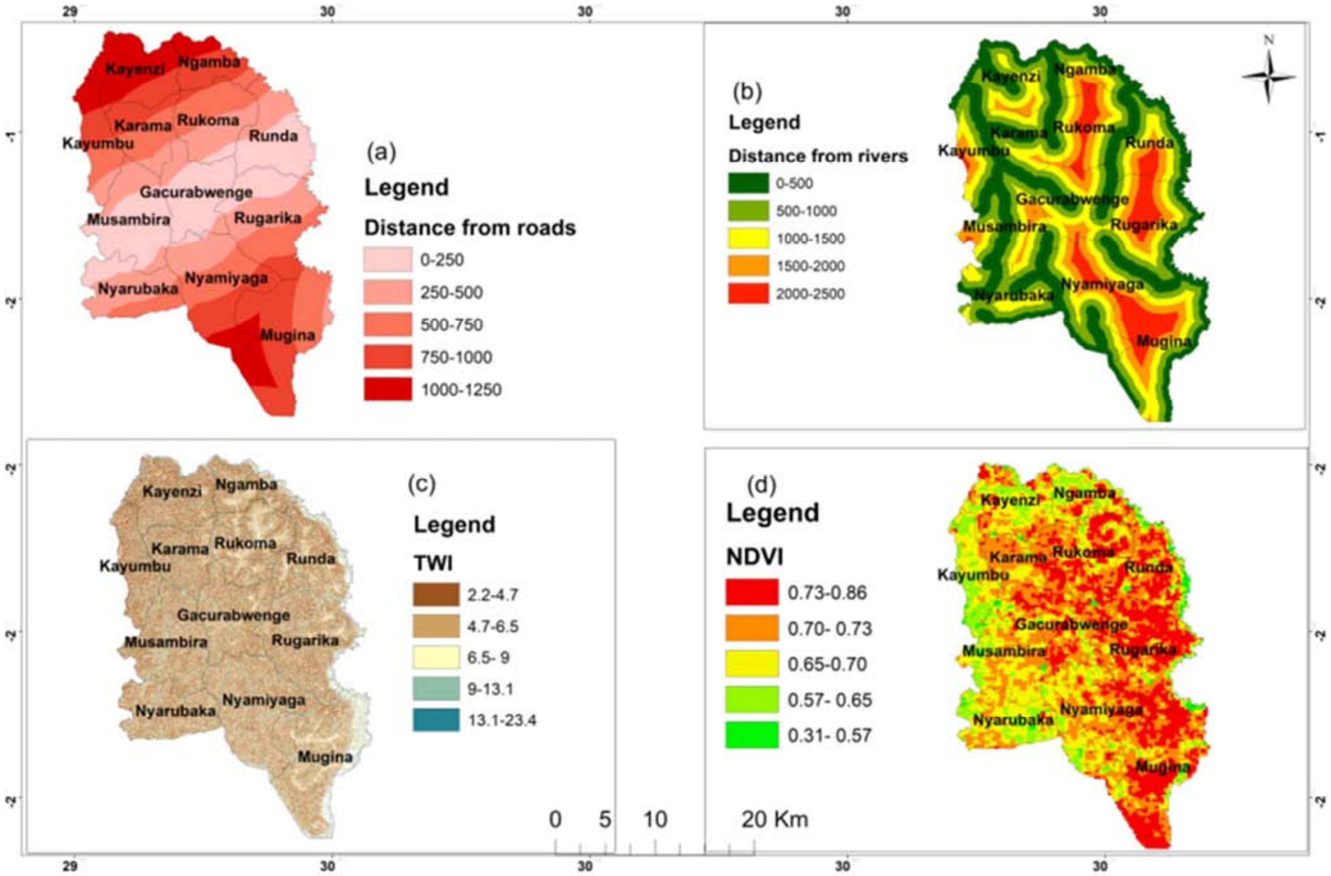

Figure 3. Flood causal factors namely (a) distance to roads, (b) distance from rivers, (c) Topographic Wetness Index and (d) Normalized Difference Vegetation Index.

Finally, the study utilized the lithology and soil texture. It was noted that granite is the dominating lithological class in the study area, mainly in Karama, Gacurabwenge, Kayumbu, Musambira, Nyarubaka, Nyamiyaga, Karama and Kayenzi sectors (Figure 3a). The obtained soil texture classes (Figure 4b indicated that clay loam is the primary soil classes found in the district of Kamonyi. The above ten factors were then employed to map flood hazard and spatially differentiate flood prone and safe zones across the study area.

2.2.2. Datasets on Recent Flood Events

The authors employed secondary data related to losses registered due to recent flood events which took place within the study area. These consisted mainly on killed/injured people, damaged cropland, destroyed houses/items, destroyed infrastructures like roads, bridges and schools and hospitals. These datasets were collected from the Rwanda's Ministry in Charge of Emergency Management (MINEMA). These recent flood losses ranged from 2013 to 2020.

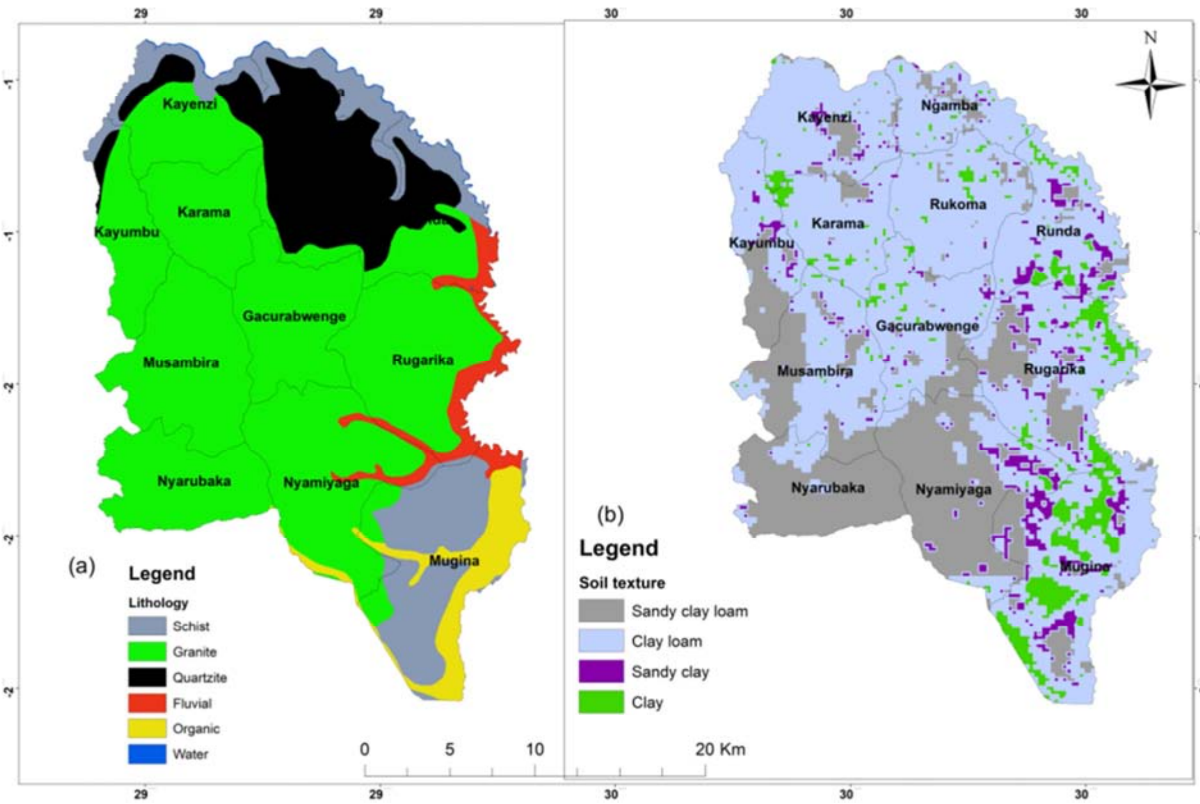

Figure 4. Flood causal factors: (a) lithology and (b) soil texture.

2.3. Data Analysis

2.3.1. Mapping Flood Hazard and Its Triggering Factors

To determine the flood hazard safe and/or prone areas, two stages were undertaken. The first step was the analysis and highlighting major factors which cause flood in Kamonyi district. The last step consisted in mapping flood hazard and the step was completed by applying the Spatial Analyst Tools (Fuzzy weighting) in GIS software. The above ten factors were then employed to map flood hazard and spatially differentiate flood prone and safe zones across the study area. The produced map was subdivided into five classes namely very high, high, moderate, low and very low flood hazard.

2.3.2. Prediction of Future Occurrence

The authors referred to recent flood by basing on each sector's record from 2013 to 2020. The Microsoft Excel was employed to indicate and predict flood losses over the study area. The predicted flood occurrence ranged from 2020 to 2050 and its respective map was produced. The methodological framework adopted by this research was illustrated in Figure 5.

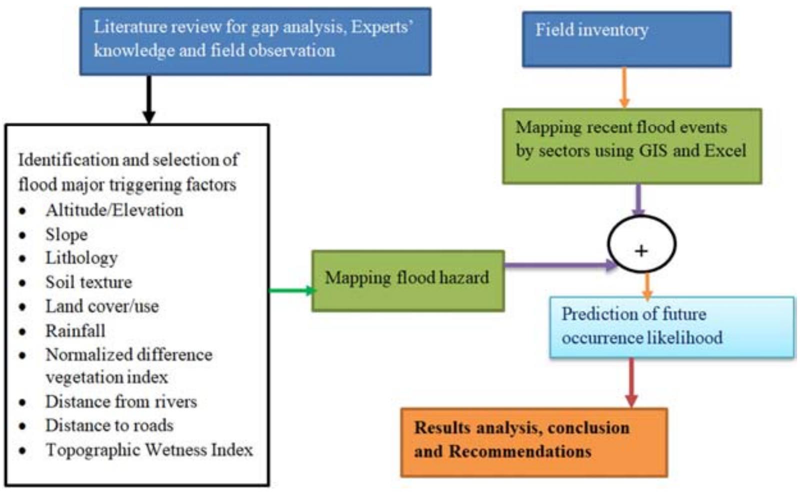

Figure 5. Research methodological framework.

3. Results

3.1. Mapping Flood Hazard

The results in Figure 6 demonstrated that Rukoma, Gacurabwenge, Musambira, Nyarubaka and Kayumbu sectors are classified in the high and very high flood hazard zone. The results also showed that Rugarika, Nyamiyaga and Rugina sectors of Kamonyi district are in the very low, low and moderate flood hazard classes.

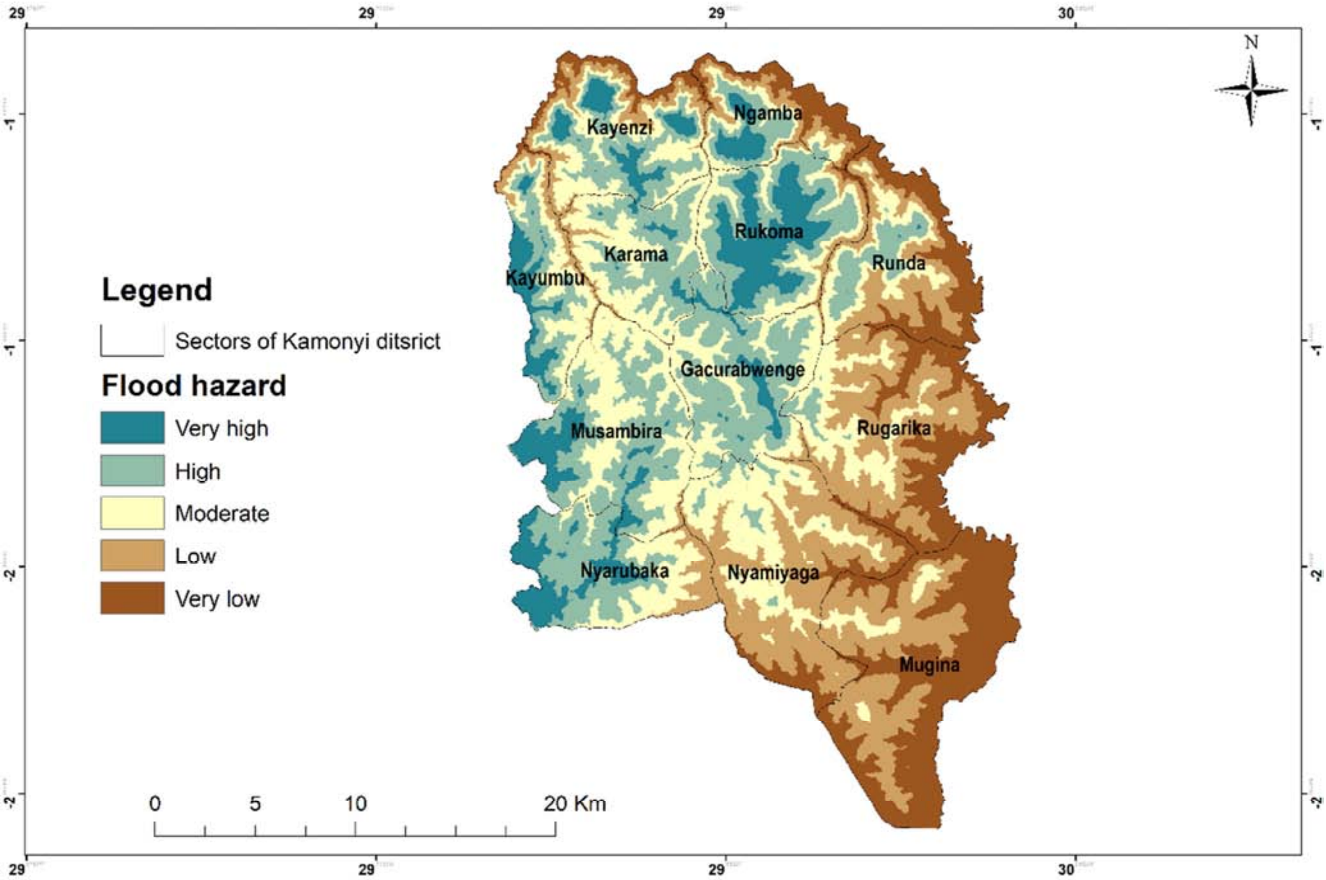

Figure 6. Flood hazard in Kamonyi district.

The results in Figure 7 indicated that elevation, slope and rainfall are the major factors triggering the occurrence of flood in Kamonyi district.

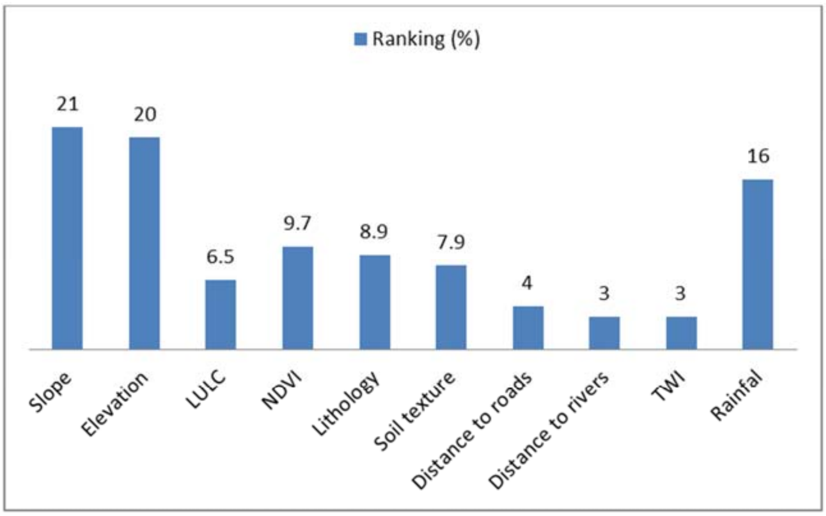

Figure 7. Estimated contribution of flood triggering factors.

3.2. Prediction of Flood Occurrence

The authors based on current flood hazard (Figure 6) distribution in Kamonyi district and then tried to predict its future occurrence likelihood in this area. The results in Table 1 indicated that Karama and Rugarika sectors recorded high number (265.5 and 234, respectively) of flood events between 2013 and 2020.

Table 1. Flood cases per sector (2013-2020).

No.	Sectors	Deaths	Injuries	Houses destroyed	Cropland damaged Ha	Road damaged	Elec. line damaged	Water line damaged	Lost livestock	Total
1	Gacurabwenge	0	1	7	3	0	9	2	0	22
2	Karama	5	12	230	18.5	0	0	0	0	265.5
3	Kayenzi	0	0	2	0	0	0	0	0	2
4	Kayumbu	2	4	7	0	2	0	0	0	15
5	Rugarika	1	4	209	18.2	1	0	1	0	234.2
6	Musambira	0	0	6	1	0	0	0	0	7
7	Ngamba	0	0	13	14	0	0	0	0	27
8	Nyamiyaga	0	0	19	0	0	0	0	0	19
9	Mugina	0	1	58	7	0	0	0	0	66
10	Nyarubaka	0	0	26	0	0	0	0	0	26
11	Rukoma	0	1	35	11	0	8	0	0	55
12	Runda	5	0	110	31	0	0	0	0	146

The authors predicted the likelihood of flood occurrence in Kamonyi district with reference to its current flood hazard distribution (Figure 6) and recent losses recorded per each sector the study area (Table 1). The estimated flood occurrence prediction between 2020 and 2050 in sectors of Kamonyi district is distributed in Figure 8.

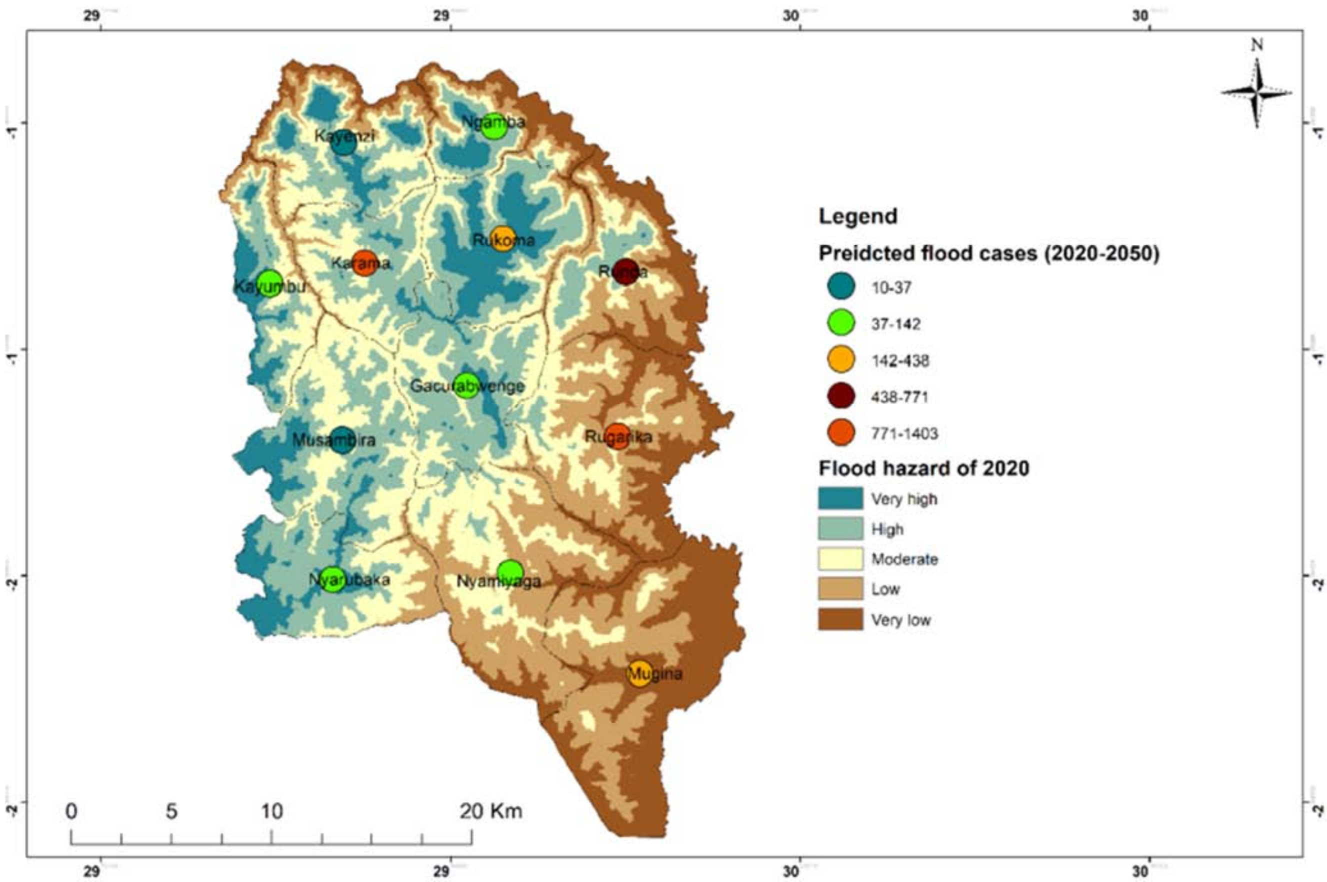

Figure 8. Predicted flood occurrence.

The flood occurrence prediction in Figure 8 indicated that Karama and Rugarika sectors are highly prone to future flood occurrence since they are predicted to register flood cases (number of deaths and injuries, destroyed houses and damaged croplands, road and electrical lines damaged, and lost livestock) ranging between 1,200 and 1,400 from 2020 to 2050, respectively.

Table 2. Predicted flood cases per sector 2020-2050.

No.	Sectors	2013-2020	Annual case	2030	2050
1	Gacurabwenge	22	3.142	53.428	116.285
2	Karama	265.5	37.928	644.785	1403.357
3	Kayenzi	2	0.285	4.857	10.571
4	Kayumbu	15	2.142	36.428	79.285
5	Rugarika	234.2	33.457	568.771	1237.914
6	Musambira	7	1	17	37
7	Ngamba	27	3.857	65.571	142.714
8	Nyamiyaga	19	2.714	46.142	100.428
9	Mugina	66	9.428	160.285	348.857
10	Nyarubaka	26	3.714	63.142	137.428
11	Rukoma	55	7.857	133.571	290.7142
12	Runda	146	20.857	354.571	771.714

The results in Table 2 indicated that between 2013 and 2020, each sector recorded an annual increase in flood cases (number of deaths and injuries, destroyed houses and damaged croplands, road and electrical lines damaged, and lost livestock). However, if current conditions exist until 2050, there will be increased number of flood cases which result in killing people, damaging their cropland and infrastructures. The prediction showed that Karama and Rugarika sectors will record advancing number of flood cases in 644.78 and 568.77 in 2030 up to 1403.35 and 1237.92 in 2050, respectively.

4. Discussion

In Rwanda since 1960, flood has been under experience, and its occurrence has caused considerable cropland damages, destroyed houses, bridges and roads and other infrastructures. The flooding also killed, injured some people and others were left homeless, and the largely affected were those in grouped settlements in and/or close to wetlands [3, 4]. As previously reported, for flood risk reduction, it is good to map flood hazard which differentiates the flood hazard and prone areas by ensuring the usage of high number of flood occurrence triggering factors [1, 18]. This study employed ten factors (see section 2.2.1), which is the case of several studies which employed similar number of triggering indicating that the more factors, the higher accurate flood mapping.

The results of this study indicated that elevation, slope and rainfall are the major parameters triggering the occurrence of flood in Kamonyi district. These factors ranked 21, 20 and 16 percent, respectively (Figure 7). In addition, the results in Figures 6 and 7 indicated each sector's exposure to flood and the major causal factors. This expresses that for reducing the impact of flood in Kamonyi district, it would be good to consider each sector's record. The reduction of flood risk focuses on lowering the consequences of flood by employing all possible measures across the vulnerable areas. The policies include not limited to flood forecasting and warning system, evacuation and disaster management plans [19, 20].

However, the foremost step that has been highlighted toward flood risk reduction is the engagement and participation of the local community in the planning, designing and implementation of flood risk reduction [19]. For this study, as indicated in Table 2, from 2013 to 2020, each sector of Kamonyi district has experience flood in its own way. The Karama and Rugarika sectors registered 265 and 234 flood cases, respectively and low number of flood cases was noticed in Kayenzi and Musambira sectors (Table 2). Additionally, the results in Figure 8 confirmed that in 2050, both Karama and Rugarika sectors will be highly prone to flood since they will register an estimated number of flood cases ranging between 1,200 and 1,400 from 2020 to 2050.

This expresses that if policy makers plan to minimize flood risk in Kamonyi district, it is good to consider the flood causal factors mainly elevation, rainfall and slope (Figure 7) by minimizing the runoff. In addition, the predicted sectors which will record high number of flood cases (Table 2 and Figure 8) need special attention by informing the residents of both sectors so that the causal factors can be minimized.

5. Conclusion

This study employed secondary data on flood causal factors namely: elevation, slope, rainfall, land use and land cover (LULC), Normalized Difference Vegetation Index (NDVI), Topographic Wetness Index (TWI), distance from roads, distance from rivers, lithology and soil texture. The Fuzzy Overlay method of the Spatial Analyst Tools in the Geographic Information System (GIS) was employed. The spatial distribution of flood hazard marked the Rukoma, Gacurabwenge, Musambira, Nyarubaka and Kayumbu sectors as highly prone to flood mainly due to elevation, slope and rainfall. Recent flood cases (killed and injured people, damaged cropland and roads, destroyed houses along with the damaged electrical and water line) between January 2013 and April 2020 were used. It was revealed that Karama and Rugarika sectors recorded high number of previous flood cases. Regarding the prediction estimated from 2020 to 2050, Karama and Rugarika sectors as the areas likely exposed to future flood occurrence. It is concluded that policy makers can consider each sector's record and rainwater harvesting along with development of terraces would help to minimize the runoff. In addition, timely rainfall information sharing and its accessibility would reduce the damages of flood in this area. Future studies are recommended to analyze the relationship between population settlement and flood occurrence since Kamonyi district is a peri-urban zone under increasing resident rate.

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