FLOOD RISK MAPPING USING GIS-BASED MULTI-CRITERIA ANALYSIS: SONGINOKHAIRKHAN DISTRICT CASE STUDY

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KEYWORDS: Flood risk mapping, GIS-based multi-criteria analysis, AHP, Flood modeling

ABSTRACT: Accurate flood risk assessment and mapping is one of the principal components of flood monitoring and prevention in urban areas. The aim of this study is to develop accurate flood risk maps in Songinokhairkhan district, Ulaanbaatar. In this study, the potential flood risk areas in the Songinokhairkhan district were identified using Geographical Information Systems (GIS)-based multi-criteria analysis along with the utilization of Analytical Hierarchy Process method to define the optimal weights for the criteria that contribute to flood risk. In addition, the flood models were developed using Hydrologic Engineering Center's River Analysis System (HEC-RAS) software in the catchment areas that identified as flood risk areas by GIS-based multi-criteria analysis. Using these models, we estimated the total area to be flooded, total residential area to be flooded, and total unit-areas to be flooded in event of flood. As a result, 0.55% or 6.70 km^2 area of Songinokhairkhan district is determined to be at very high flood risk, 8.32% or 99.78 km^2 is determined to be at high flood risk. Plus, three catchment areas are considered to have the high flood risk.

1. INTRODUCTION

A flood is a natural disaster, which the water level rises above normal levels, causing rapid flow along dry riverbeds and ravines and fills the adjacent low-lying lands that are usually dry, producing significant social, economic, and environmental impacts (National Geographic, 2019), including: loss of human life, negative effects on the population, damage to the infrastructure and essential services, damage to crops and animals, the spread of diseases, and contamination of the water supply. Extreme weather conditions increase the probability of disasters that may cause unusual and unexpected events such as flooding and flood-related hazards (G. Zhao, 2019). Many factors contribute to floods: heavy rains, the melting of snow pack, and land-use change, such as deforestation and urbanization are some important factors (D. Rincón, 2018). Globally, the frequency, damage, and impact of floods are increasing in the last thirty years (S. P. Ozkan, 2016), mainly due to climate change and land-use activities. In Mongolia, especially in Ulaanbaatar, floods are the most common natural disaster and provides heavy damage due to poorly planned and undeveloped residential areas, densely populated ger districts, substandard flood protection facilities, and improper land-use activities. In the last ten years, the number of flood events has increased by 4.3-fold in Ulaanbaatar (G. Perliimaa, 2020). To prevent and mitigate flood danger, the flood risk maps has become one of the important tools (S. P. Ozkan).

The purpose of this study is to develop accurate and updated flood risk maps in Songinokhairkhan district, Ulaanbaatar, Mongolia. Songinokhairkhan district has a high frequency of flood events and great damage, which tends to increase due to ger district sprawl, and lack of flood protection systems and infrastructure. Therefore, it is necessary to prevent the increasing flood risk in Songinokhairkhan district and reduce flood vulnerability and damage by identifying and estimating flood risk areas using GIS, Remote Sensing, and Spatial Analysis methods. In this study, we used the geographical information systems (GIS) with multi-criteria decision making (MCDM), so-called GIS-Based multi-criteria analysis. This GIS-based multi-criteria approach has been increasingly used for flood risk assessment, as it presents several advantages (R. Albano, 2017). The main advantage of this methodology is the possibility of obtaining a reliable flood risk map with a relatively low monetary and time investment. In addition, it is easy to update, uses easy-to-get open-source input data, and is flexible in terms of which criteria are included (D. Rincón, 2018).

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) software (G.W. Brunner, 2016) developed by the U.S. Army Corps of Engineers (USACE) is generally used for investigating flooding and flood-related hazards, and for identifying floodplains globally (N. Devi, 2019; D. Aryal, 2020). We used the HEC-RAS software to create flood models, moreover, to estimate the areas to be flooded, the residential areas to be flooded, and the unit-areas to be flooded in a certain amount of rainfall over a certain period of time. The paper is organized as follows. The study area is introduced in Section 2. Then the methodology is described in Section 3, followed by results in Section 4, and conclusion in Section 5.

2. STUDY AREA

Songinokhairkhan is one of nine districts of Mongolian capital of Ulaanbaatar. It is subdivided into 32 subdistricts (so-called khoroo). Songinokhairkhan is located in the west, at the foot of one of the four mountains of Ulaanbaatar, the Songino Khairkhan Uul. The district has area of 1200.6 km^2 and population of 335703 in 2020, making it the second largest of Ulaanbaatar's central districts. This is one of the key industrial centers of the city, home to major processing plants and construction yards. The rainy season is from June to August, accounting for 80% of the total annual rainfall. The boundary of Songinokhairkhan district is shown in Figure 1.

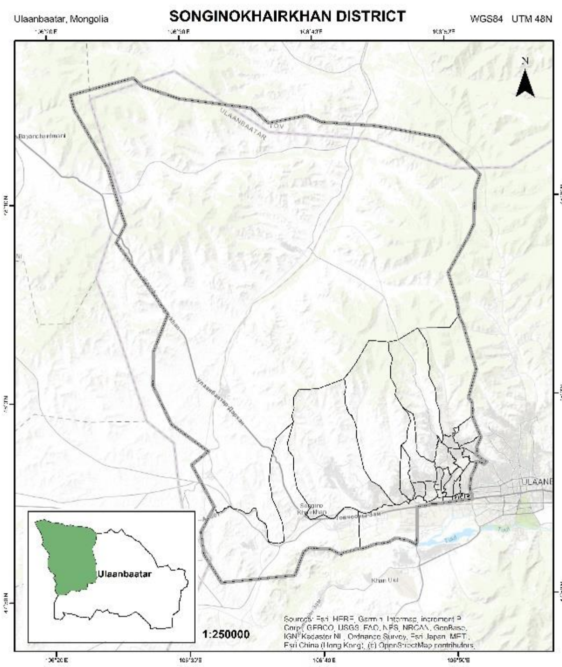


Figure 1. Songinokhairkhan district boundary

3. METHODOLOGY

Within the framework of the study, the flood risk map of Songinokhairkhan district generated using GIS-based multi-criteria analysis, and the flood models of very high flood risk areas developed using HEC-RAS software. The methodology workflow is shown in Figure 2.

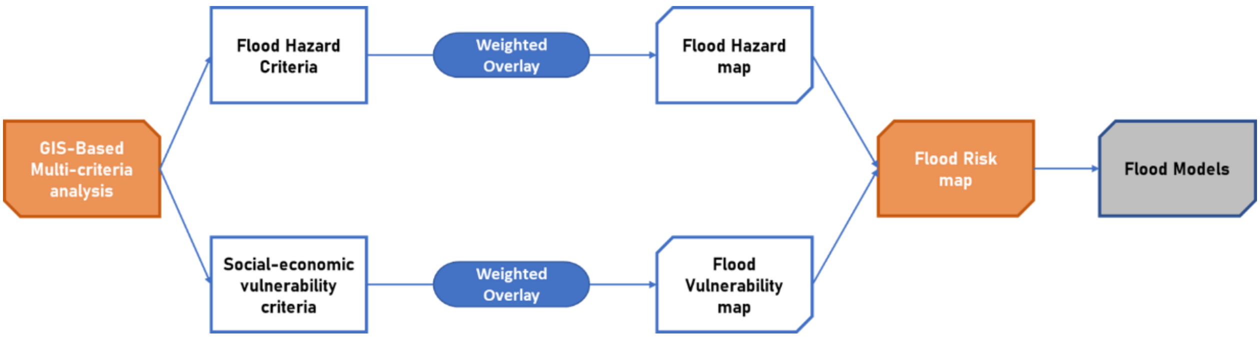


Figure 2. Methodology workflow overview

3.1 GIS-based Multi-Criteria Analysis

The GIS-based multi-criteria approach for flood risk assessment is based on the spatial intersection of two components: flood hazard and social-economic vulnerability (D. Rincón, 2018). As mentioned above, the Analytic Hierarchy Process (AHP) was selected as a method of weighting criteria in the context of multi-criteria decision making (MCDM). The result of this method is a flood risk map showing the spatial distribution of flood risk and its intensity level.

3.1.1 Flood hazard and social-economic vulnerability criteria: In order to identify flood risk areas in Songinokhairkhan district using GIS-based multi-criteria analysis, seven flood hazard criteria and five social-economic vulnerability criteria were proposed, and each criterion was categorized and mapped at classes 1-5. The criteria taking into account for evaluating the flood hazard are: Distance to streams (DS), distance from drainage (DD), total precipitation (TP), density of ravines (DR), slope (S), flow accumulation (FAC), elevation (H). The criteria taking into account for evaluating the social-economic vulnerability are: Population density (PD), settlement type (ST), population aged 0-4 and 70+ (PA), number of uneducated people (UE), number of people with disabilities (PD). The flood hazard and vulnerability criteria, its level classes and values are shown in Table 1 and Table 2, respectively.

Table 1. Classes of criteria that contribute to flood hazard

Class	Level	Criteria for Flood Hazard						
		DS (m)	**DD (m)**	**TP (mm)**	**DR (ravine/ha)**	**S (degree)**	**FAC (cm)**	**H (m)**
5	Very high	< 100	1000 <	360 <	1.6 <	0 - 3.6	113-299	1100-1280
4	High	100-300	500-1000	344-350	1.1-1.6	3.6-9.6	53-113	1280-1370
3	Medium	300-500	300-500	338-344	0.6-1.1	9.6-16.2	21-53	1370-1460
2	Low	500-1000	100-300	330-338	0.2-0.6	16.2-24.6	5-21	1460-1550
1	Very low	1000 <	< 100	< 330	< 0.2	24.6 <	< 5	1500 <

Table 2. Classes of criteria that contribute to social-economic vulnerability

Class	Level	Criteria for Social-economic Vulnerability				
		PD (people/km^2)	**ST**	**PA**	**UE**	**PD**
5	Very high	15000 <	Ger	1400 <	8140 <	255 <
4	High	8400-15000	-	1150-1400	6510-8140	202-255
3	Medium	3600-8400	Low-rise building	900-1150	5080-6510	154-202
2	Low	1600-3600	Apartment complex	650-900	3320-5080	125-154
1	Very low	< 1600	No settlement	< 650	< 1650	< 50

These classes were based on values from the literature and professional expertise. These classes may be adjusted based on purpose and case of study or by decision makers.

3.1.2 Determining criteria weights: The weight on the risk assessment of each criterion was determined using the AHP method. AHP, developed by Saaty in 1990 (T. L. Saaty, 1990), is one of the several criteria weighting methods of MCDM (D. Rincón, 2018). This method allows comparing two criteria at a time through a pairwise comparison matrix in which the values of relative importance from one criterion over another criterion are assigned (D. Rincón, 2018). The standardized scale of relative importance ranges between 1 and 9, where 1 is equal importance, and 9 is extreme importance. AHP has been used worldwide in a wide range of fields such as industry, education, transportation, and healthcare, among others, especially due to its application in group decision making (M. Majumer, 2015).

The first step for determining the weights of the criteria using the AHP method is to assign the values of importance from one criterion over another criterion on a scale from 1 to 9 (T. L. Saaty, 1990). The importance values for flood hazard and social-economic vulnerability were based on the literature review and self-criteria in this study. The next step is to build the pairwise comparison matrix where in each cell, every criterion is assigned an intensity of importance over another. Each criterion is compared with the other criteria. The next step is to create a linear normalization of the pairwise comparison matrix. All of the values from each column are summed, and then each element of the matrix is divided by its total. Finally, the weights are obtained by computing the average of each row of the normalized values of the matrix. The weights of the Songinokhairkhan district's flood hazard and social-economic vulnerability criteria determined by this method are shown in Table 3 and Table 4, respectively.

Table 3. Weights of flood hazard criteria

Criterion	Weights
Distance to streams	0.213
Distance from drainage	0.213
Total precipitation	0.213
Density of ravines	0.121
Slope	0.070
Flow accumulation	0.070
Elevation	0.070
$\sum$	**1.000**

Table 4. Weights of social-economic vulnerability criteria

Criterion	Weights
Population density	0.300
Settlement type	0.300
Population aged 0-4 and 70+	0.192
Number of uneducated people	0.104
Number of people with disabilities	0.104
$\sum$	**1.000**

3.1.3 Weighted overlay: For each of the flood hazard and vulnerability criteria, layers classified at 1-5 classes were created. Then the flood hazard and vulnerability maps were generated by overlaying them by their weights determined by the AHP method, so-called Weighted Overlay. Weighted overlay is one method of modeling suitability. It is act of multiplying each raster cell's value by its layer weight and totaling the values to derive an output value. The Weighted Overlay formula is shown in Equation 1.

$$Weighted\ Overlay = \sum(Xi * Wi) \qquad (1)$$

Where Xi is the cell value of raster and Wi is the corresponding weight. At last, the flood risk map of Songinokhairkhan district was generated as a spatial overlay (equal weights) between the vulnerability map and the flood hazard map.

3.2 Flood Modeling

Flood models were developed using HEC-RAS software in the catchment areas of very high flood risk areas in Songinokhairkhan district, which defined by the GIS-Based multi-criteria analysis. By creating this model, it will be possible to estimate the total area to be flooded, the residential area to be flooded, and the unit-areas to be flooded in the event of flood.

HECRAS - 2D Unsteady Flow tool was used to create flood models. The input data required for creating flood model was the digital elevation model (DEM) with a ground resolution of 10 m × 10 m and vector files of catchment area boundary. As a result, a series of flood time data was generated in the catchment areas of very high flood risk areas of Songinokhairkhan district. From this data, we estimated the total area to be flooded, the residential area to be flooded, and the number of unit-areas to be flooded in a certain amount of rainfall over a certain period of time.

4. RESULTS

4.1 Generation of flood hazard map

In order to generate flood hazard map of Songinokhairkhan district by using GIS-based multi-criteria analysis, seven flood hazard criteria were proposed (Table 1). For each criterion, classified maps were created. Figure 3 presents the classified maps and highlights the levels from very low to very high for each criterion.

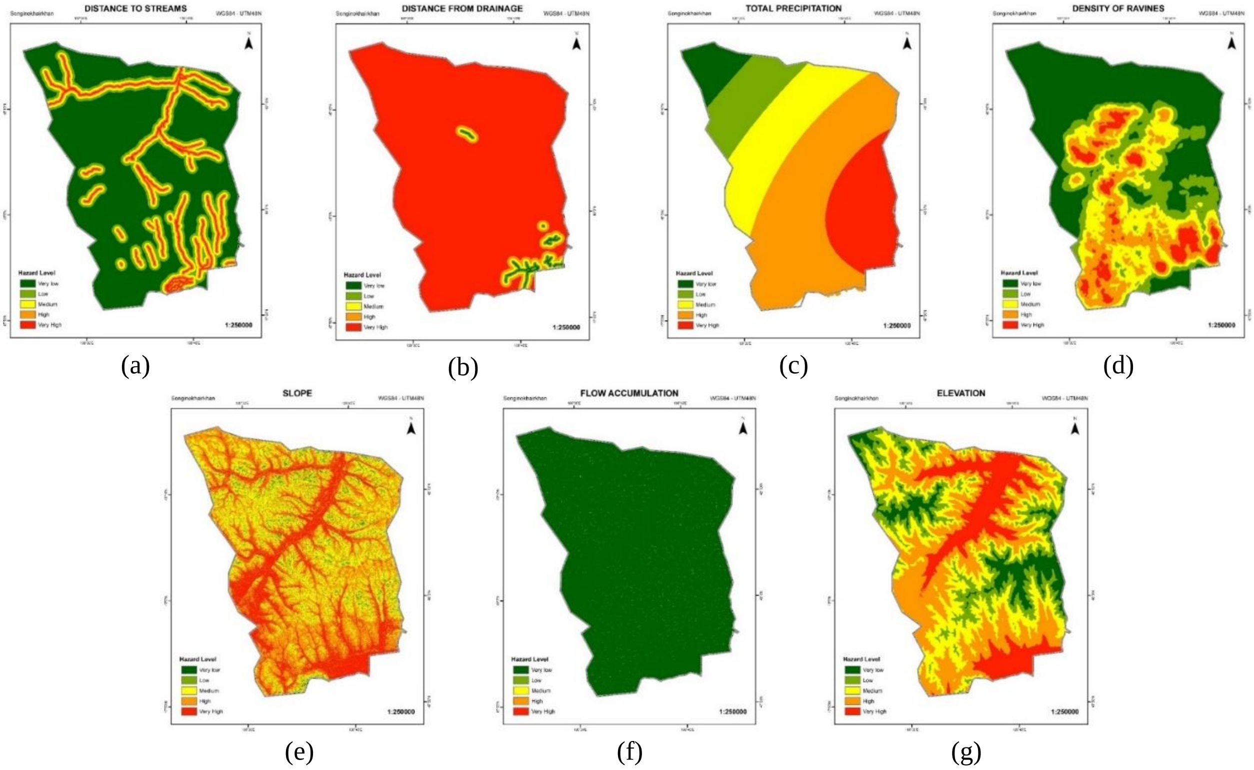


Figure 3. Flood Hazard criteria: (a) distance to streams; (b) distance from drainage; (c) total precipitation; (d) density of ravines; (e) slope; (f) flow accumulation; (g) elevation

The classified maps of each criterion were overlayed by their corresponding weights to generate flood hazard map of the district. The flood hazard map of Songinokhairkhan district is shown in Figure 4.

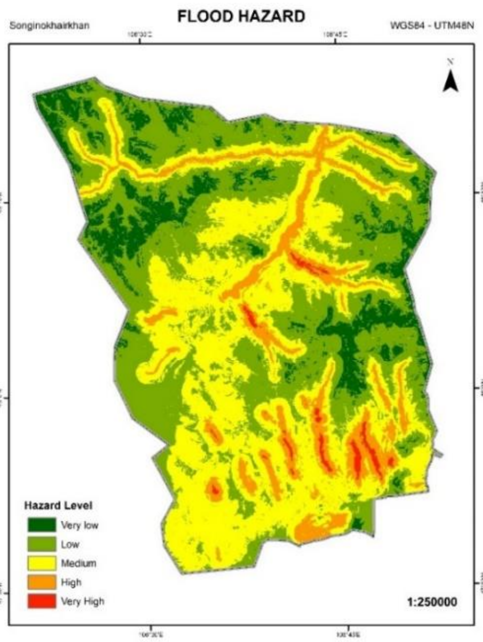
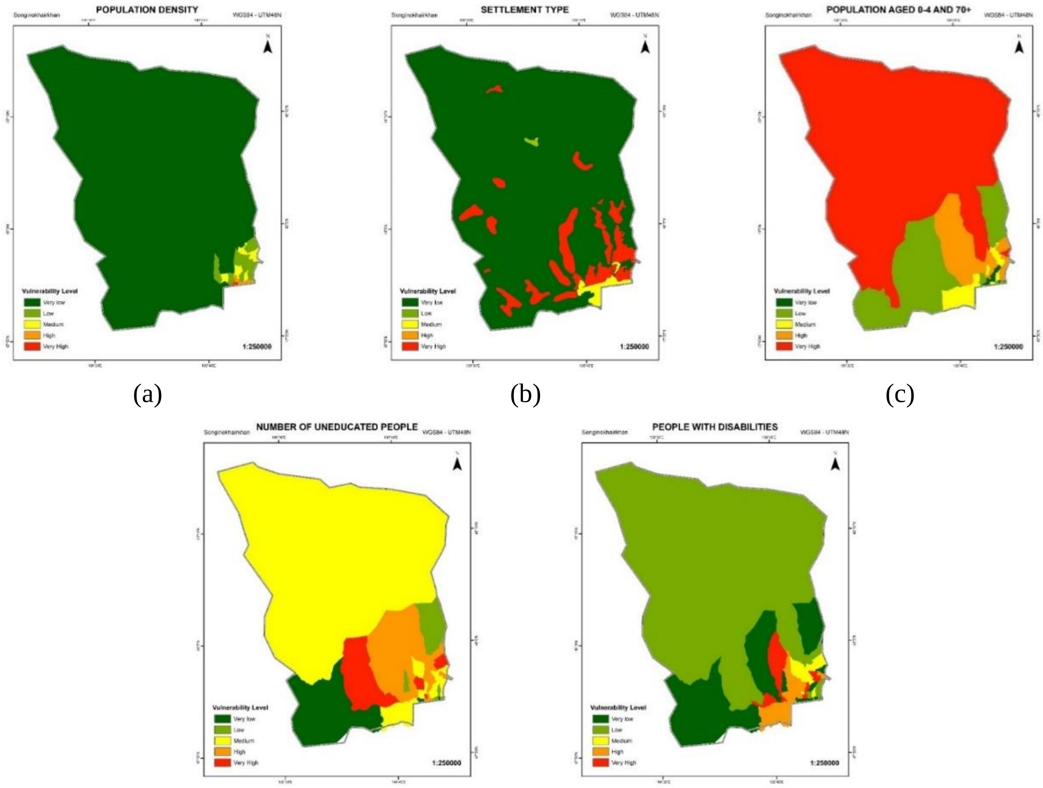


Figure 4. Flood hazard map of Songinokhairkhan district

4.2 Generation of vulnerability map

For each social-economic criterion (Table 2), classified maps were created. Figure 5 presents the classified maps and highlights the levels from very low to very high for each criterion.



(a) (b) (c)

(d) (e)

Figure 5. Social-Economic Vulnerability criteria: (a) population density; (b) settlement type; (c) population aged 0-4 and 70+; (d) number of uneducated people; (e) people with disabilities

Using the weighted overlay of classified maps of each social-economic criterion, the flood vulnerability map was generated. Flood vulnerability map of Songinokhairkhan district is shown in Figure 6.

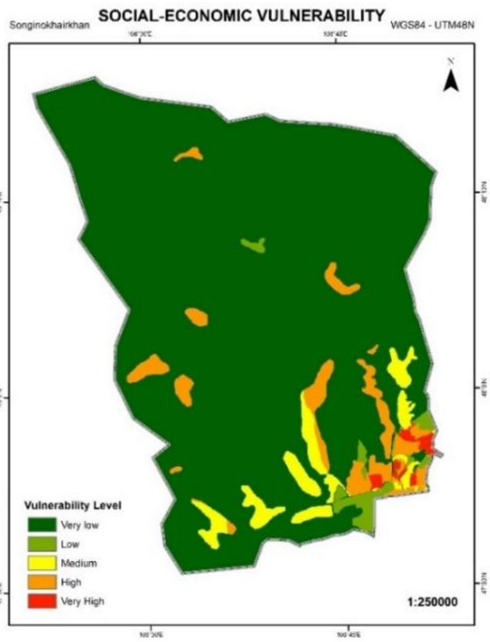


Figure 6. Social-Economic Vulnerability map of Songinokhairkhan district

4.3 Generation of flood risk map

Flood risk map of Songinokhairkhan district was generated as a spatial overlay (equal weights) between flood hazard map (Fig. 4) and vulnerability map (Fig. 6). Figure 7 presents the Flood risk map of Songinokhairkhan district. Figure 8 shows catchment areas considered to have a very high flood risk. The flood risk map (R) based on flood hazard (H) and social-economic vulnerability (V) is derived from Equation 2.

$$R = H \cap V \qquad (2)$$

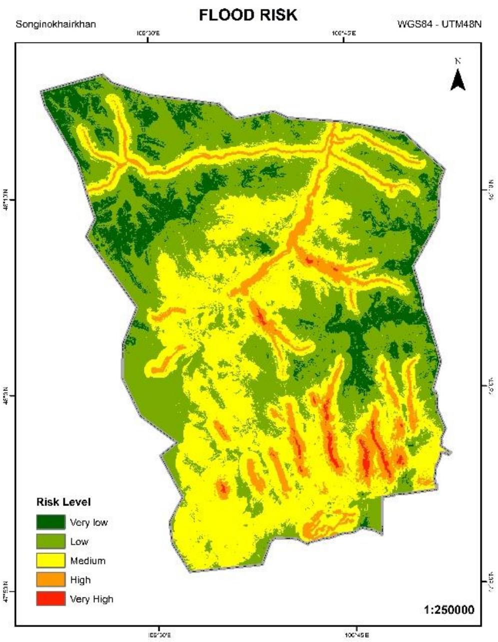


Figure 7. Flood risk map of Songinokhairkhan district

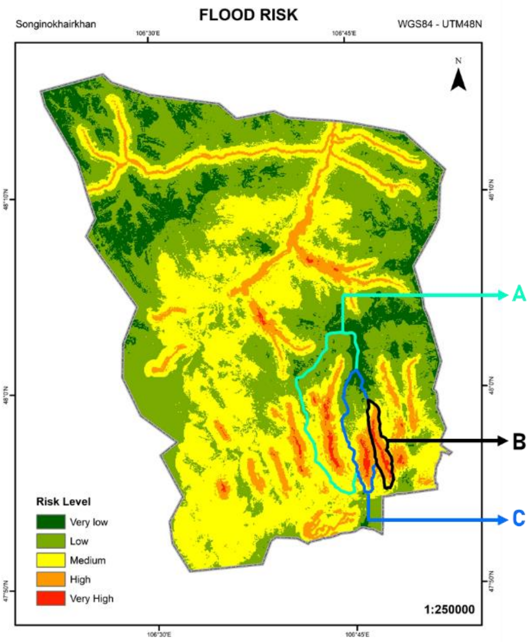


Figure 8. Very high flood risk catchment areas

The flood risk map of Songinokhairkhan district shows that there is a very high flood risk in Bayangol catchment area (**A)**, Tahilt River catchment area **(B)**, and Tolgoit Baga Narangiin Am catchment area **(C)**.

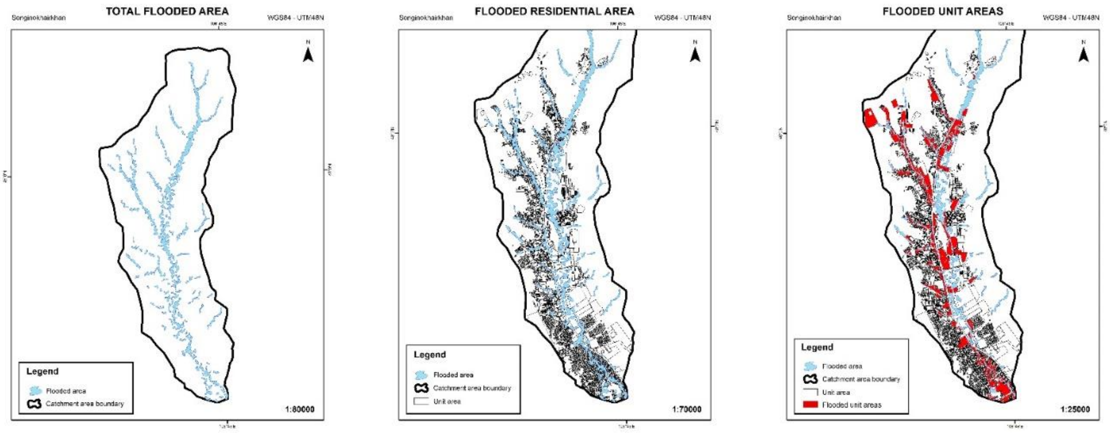
4.4 Flood modeling results

Flood modeling was performed in areas that classified as very high flood risk in flood risk map, such as Bayangol catchment area (**A**), Tahilt River catchment area **(B)**, and Tolgoit Baga Narangiin Am catchment area **(C)**. Using flood models, the amount and flow of floods caused by 10-40 mm of heavy rainfall for 30 minutes at these catchment areas were determined. The total flooded area, the flooded residential area, and the number of flooded unit-areas were estimated from flood models of very high flood risk areas in Songinokhairkhan district and presented in Table 5.

Table 5. Result of Flood modeling

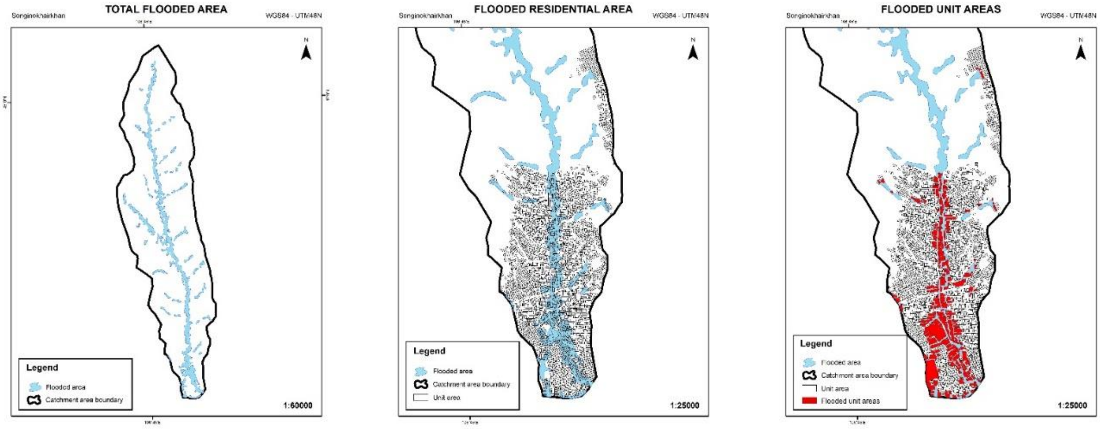
	Bayangol	**Tahilt River**	**Tolgoit Baga Narangiin Am**
Total flooded area	4.323 km^2	2.238 km^2	1.058 km^2
Flooded residential area	3.613 km^2	0.542 km^2	0.496 km^2
Number of flooded unit areas	1783	833	832

Figure 9, Figure 10, and Figure 11 show the total flooded area, the flooded residential area, and the flooded unit-areas of Bayangol catchment area, Tahilt River catchment area, and Tolgoit Baga Narangiin Am catchment area, respectively.



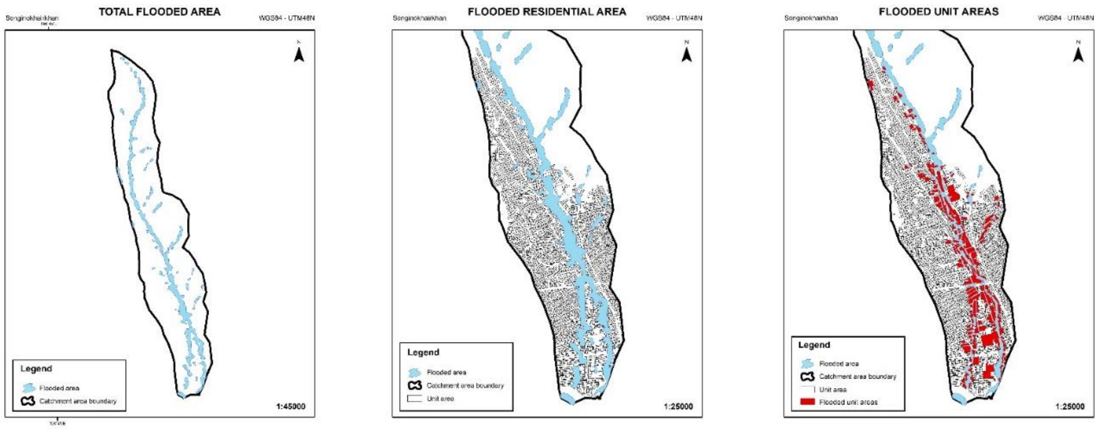
(a) (b) (c)

Figure 9. Bayangol catchment area: (a) total flooded area; (b) flooded residential area; (c) flooded unit-areas



(a) (b) (c)

Figure 10. Tahilt River catchment area: (a) total flooded area; (b) flooded residential area; (c) flooded unit-areas



(a) (b) (c)

Figure 11. Tolgoit Baga Narangiin Am catchment area: (a) total flooded area; (b) flooded residential area; (c) flooded unit-areas

5. CONCLUSION

Several studies proved that the flood risk mapping based on GIS and multi-criteria analysis is a very efficient tool for estimating areas prone to flood risk. On that account, we proposed the GIS-based multi-criteria approach to determine and identify flood risk areas in Songinokhairkhan district, Ulaanbaatar, Mongolia in this study. Accordingly, the flood risk map of Songinokhairkhan district has been generated, which can help to prevent and mitigate the flood risk.

To create the flood risk map of Songinokhairkhan district using multi-criteria analysis based on GIS, a total of 12 flood hazard and vulnerability criteria proposed. Then estimated the importance and weight of each criterion and overlaying them by weight. As a result, 0.55% or 6.70 km^2 area of Songinokhairkhan district is at very high flood risk, 8.32% or 99.78 km^2 is at high flood risk, 39.14% or 469.67 km2 is at medium flood risk, 41.21% or 494.20 km^2 is low flood risk, and the remaining 10.78% or 128.58 km^2 is classified as very low risk of flooding. Additionally, three catchment areas that are considered to have the highest flood risk were selected for flood modeling. As a result, 7.61 km^2 total area, 4.65 km^2 residential area, and 3448 unit-areas determined to be flooded in the event of flood. The results of this study indicate that this simple but effective methodology can help to reduce the danger of flooding by showing flood-prone areas as a spatial distribution. Furthermore, this method may help urban planners, land managers, water resource planners, and decision makers to focus on specific areas.

REFERENCES

- D. Aryal, L. Wang, T. Adhikari, J. Zhou, X. Li et al., 2020. A Model-Based Flood Hazard Mapping on the Southern Slope of Himalaya. Water, 12, pp. 540.
- D. Rincón, U. T. Khan, C. Armenakis, 2018. Flood Risk Mapping Using GIS and Multi-Criteria Analysis: A Greater Toronto Area Case Study. Geosciences, 8, pp. 275.
- G. Perliimaa, B. Bayartungalag, 2020. Flood Risk Mapping Using Multi-Criteria Analysis: In Case of Ulaanbaatar.
- G. Zhao, Z. Xu, B. Pang, T. Tu, L. Xu, L. Du, 2019. An Enhanced Inundation Method for Urban Flood Hazard Mapping at the Large Catchment Scale. J. Hydrol, 571, pp. 873–882.
- G.W. Brunner, 2016. HEC-RAS, River Analysis System Hydraulic Reference Manual. US Army Corps of Engineers Hydrologic Engineering Center: Davis, CA, USA, pp. 1–547
- M. Majumer, 2015. Multi Criteria Decision Making. In Impact of Urbanization on Water Shortage in Face of Climatic Aberrations. Springer: New York, NY, USA, – pp35-48.
- N. Devi, B. Sridharan, S. Kuiry, 2019. Impact of Urban Sprawl on Future Flooding in Chennai City, India Impact of Urban Sprawl on Future Flooding in Chennai City, India. J. Hydrol, 574, pp. 486–496.
- National Geographic, 2019. Floods, Retrieved April 5, 2021, from https://www.nationalgeographic.com/environment/article/floods
- R. Albano, L. Mancusi, A. Sole, J. Adamowski, 2017. Flood Risk: A collaborative free and open-source software for flood risk analysis. Geomat. Nat. Hazards Risk, 8, pp. 1812-1832.
- S. P. Ozkan, C. Tarhan, 2015. Detection of Flood Hazard in Urban Areas Using GIS: Izmir Case. In: Conference on Interdisciplinarity in Engineering.
- T. L. Saaty, 1990. How to Make a Decision: The Analytic Hierarchy Process. Eur. J. Oper. Res, 48. Pp. 9-26.