JOURNAL LA LIFESCI

VOL. 06, ISSUE 05 (463-474), 2025
DOI: 10.37899/journallalifesci.v6i5.2740

The Impact of Land Cover Change in the Bolon Watershed on Flood Zonation

Indah Permatasari Br. S. Pane[1], **Anthoni Veery Mardianta**[2], **Ahmad Perwira Mulia**[1]

[1]Department of Civil Engineering, Faculty of Engineering, Universitas Sumatera Utara, Indonesia
[2]Department of Architecture, Faculty of Engineering, Universitas Sumatera Utara, Indonesia

**Corresponding Author: Indah Permata Sari Br. S. Pane*
Email: indahsitorus96@gmail.com

Article Info

Article history:
Received 30 October 2025
Received in revised from 14 November 2025
Accepted 30 November 2025

Keywords:
AHP–WMCA C
Bolon
Watershed
Land Cover
Flood Zonation.

Abstract

Flood risk assessment plays a crucial role in determining flood hazard zones and formulating effective mitigation strategies. Using a multi-criteria decision support system, this study focuses on evaluating the flood risk index within the Bolon Watershed (DAS Bolon). Geographic Information Systems (GIS) were employed as an effective disaster mitigation tool to provide comprehensive geospatial data. The research integrates the Cellular Automata–Markov Chain (CA–MC) model using the MOLUSCE plugin in QGIS to spatially project land-use change analysis, the Analytical Hierarchy Process (AHP) to determine variable weights influencing flood risk, and Weighted Multi-Criteria Analysis (WMCA) for spatial flood zonation assessment. Between 2017 and 2021, significant land-cover changes occurred in the Bolon Watershed, with 67.55 km² converted into residential areas. Forest deforestation began in 2017 and is projected to continue until 2033, potentially disrupting the hydrological cycle and intensifying flood-prone zones. As a result, the flood-prone residential area increased markedly from 1.4% (2017) to 2.89% (2021) and is projected to reach 4.74% by 2033, with an average annual increase of 0.21%. This study underscores the importance of improved land-cover management to mitigate flood zonation in the Bolon Watershed. It also emphasizes the need for strict enforcement of spatial planning and zoning regulations, as well as enhanced monitoring and legal measures against land-use conversion particularly in flood-prone and water recharge areas.

Introduction

Flooding is one of the most frequent hydrometeorological disasters in Indonesia, especially in North Sumatra. Flooding accounts for more than 64% of all disaster events in the province. This phenomenon is caused by a combination of natural and anthropogenic factors, including extreme rainfall, vegetation cover degradation, and uncontrolled land use change (Roy et al., 2022; Weeraratna, 2022). These conditions worsen the water absorption capacity of the soil and increase the volume of surface runoff, which leads to an increase in the frequency of flooding (Deputy for Systems and Strategy, 2021; Roberts et al., 2023; Öztürk et al., 2024; Xu et al., 2022).

The Bolon River Basin (DAS) is one of the areas that has experienced rapid land use change. Settlement growth, economic activities, and deforestation have led to an increase in built-up areas, displacing water catchment areas (Msuya et al al., 2021; Adesina et al., 2025). The impact of these changes has not only reduced the region's hydrological capacity but also affected the stability of the surrounding ecosystem (Jiao et al., 2024; Liu et al., 2024). This

ISSN 2721-1304 (Print), ISSN 2721-1207 (online)

study seeks to identify the extent to which land cover change affects flood zoning in the Bolon watershed area (Kusumo & Nursari, 2016; Ocampo, 2024; Sugianto et al., 2022; Sidabutar & Sugiarto, 2025; Senan et al., 2023).

This research utilizes Geographic Information System (GIS) technology to analyze the relationship between land cover change and flood risk spatially. With the help of a Cellular Automata-Markov Chain (CA–MC) predictive model, this study can project future land conditions. The analysis was conducted by considering various variables such as rainfall, elevation, slope, and distance to rivers. This multi-criteria approach provides a more comprehensive picture of the level of flood risk faced by the study area (Mujiono et al., 2017; Rakuasa et al., 2022; Shikhteymour et al., 2023; Ibrahim et al., 2025).

The main objectives of this study are to analyze the development of land cover changes in the Bolon watershed, map changes in flood zoning in residential areas, and project future flood risk zoning. This study is expected to provide a scientific basis for adaptive and sustainable spatial planning for flood disaster mitigation in North Sumatra.

Methods

This study was conducted in the Bolon River Basin, North Sumatra. The data used included satellite images of land cover from 2017 to 2021 as well as topography, rainfall, and distance to river data. The analysis was performed using QGIS software with the MOLUSCE and WMCA plugins to comprehensively process spatial and temporal data. All data to be entered into the plugin must have coordinates, raster with pixel size, column and row locations, and the same polygon shape. The classification used in this study is as follows: 1) Bolon River Basin Polygon; 2) Raster with pixel values of 50 x 50 and 1731 columns and 1665 rows; 3) Koordinat WGS_1984_UTM_Zone_47N.

After all the data was processed, the areas that changed from 2017 to 2021 and the transition matrix from each area's data were obtained, resulting in the MOLUSCE process results.

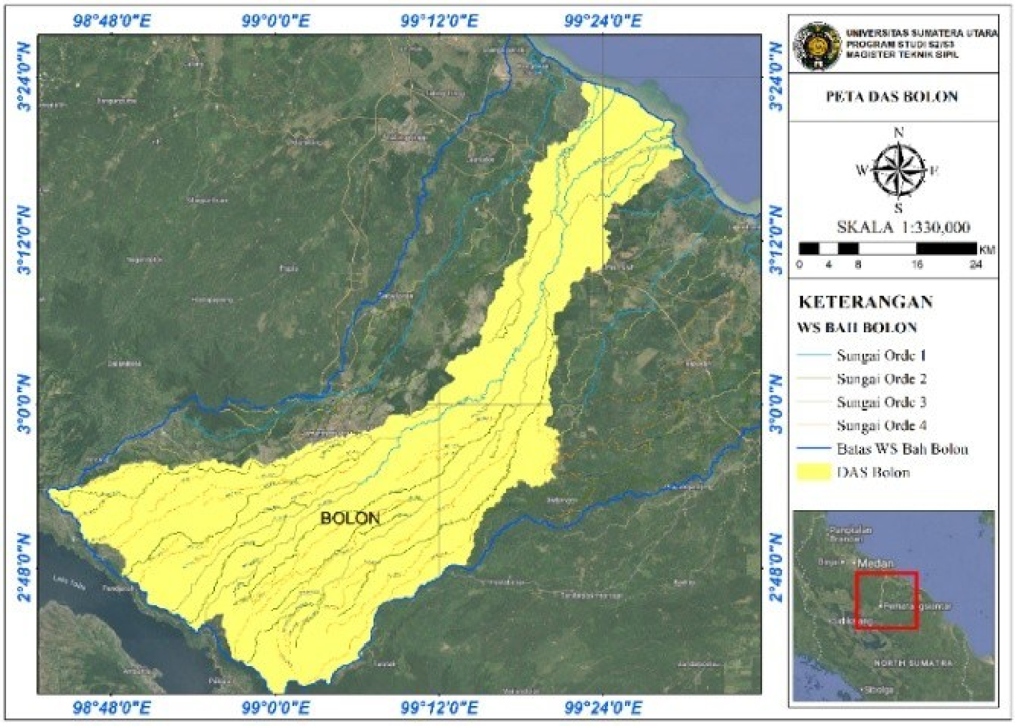


Figure 1. Map of the Bolon river basin in the Bah Bolon river area

ISSN 2721-1304 (Print), ISSN 2721-1207 (online)

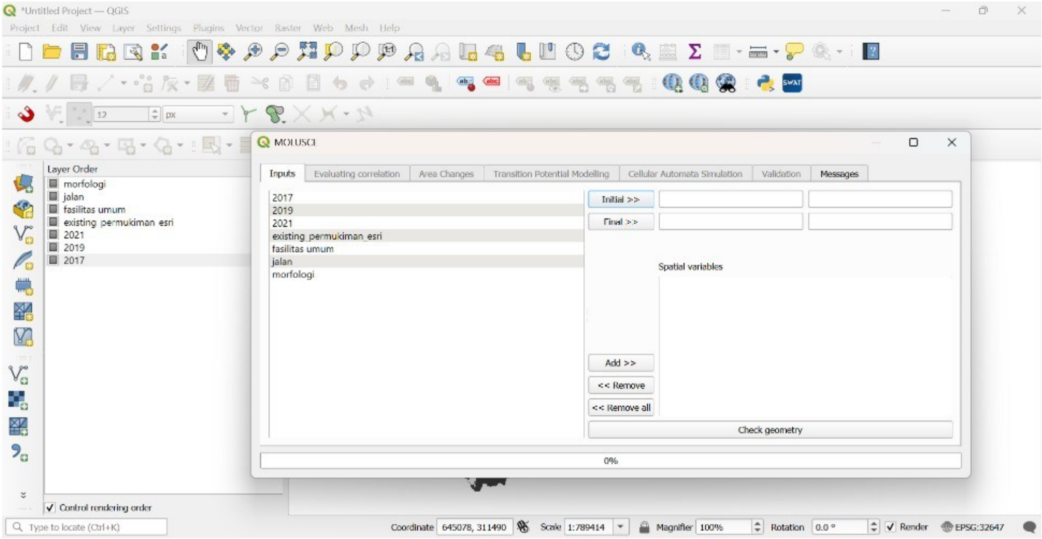


Figure 2. Input data to MOLUSCE

The Cellular Automata–Markov Chain (CA–MC) method was used to analyze land cover changes from 2017 to 2021 and predict conditions in 2033 (Gharaibeh et al., 2020). The next step used the Analytical Hierarchy Process (AHP) method to determine the weight of flood variables such as rainfall, distance from rivers, elevation, slope, and land use (Heryani, 2018). The weight values from AHP were then integrated into the Weighted Multi-Criteria Analysis (WMCA) model to produce a flood risk zoning map (Khawaldah et al., 2020). The flood risk zoning classification was divided into 5 classes by dividing the risk zone score into five intervals, namely: very low, low, moderate, high, and very high.

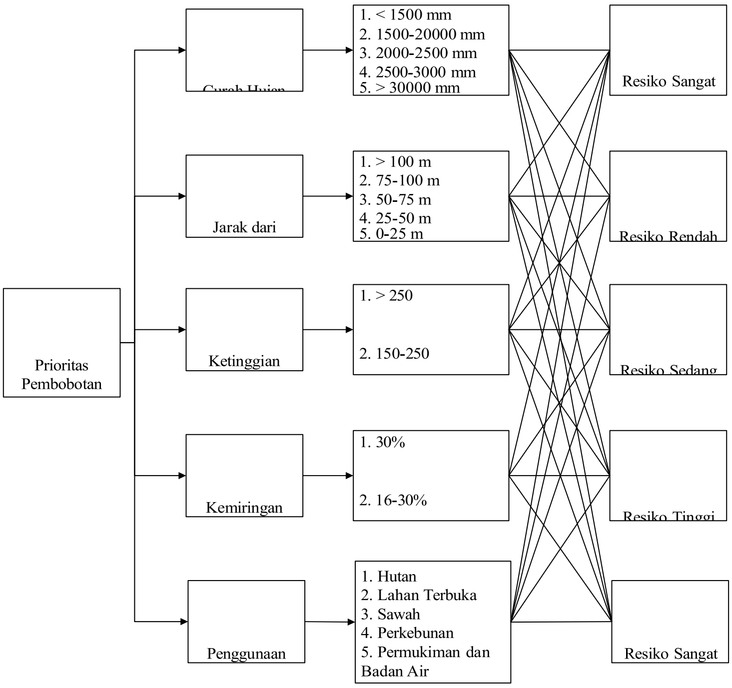


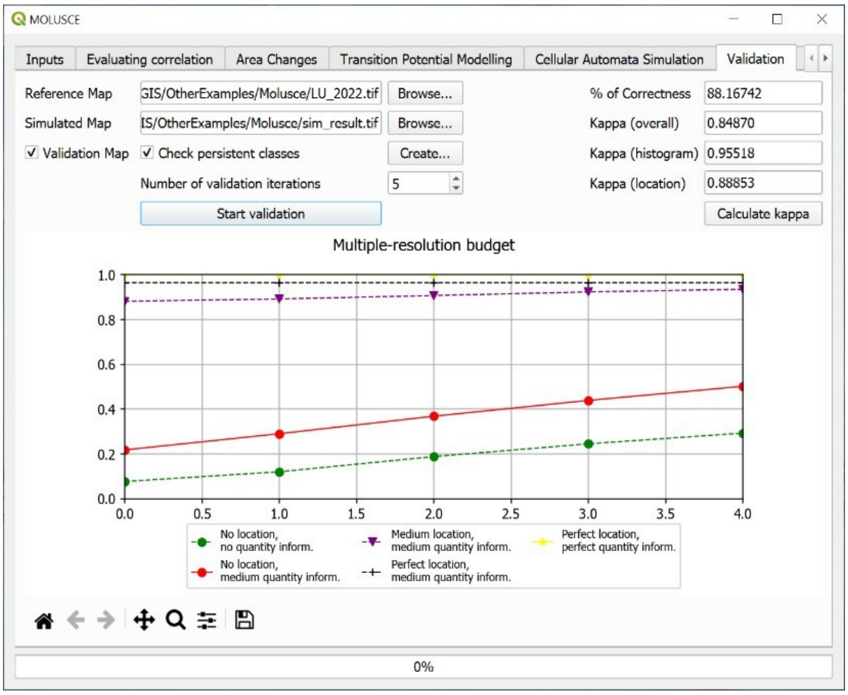
Figure 3. AHP Diagram

ISSN 2721-1304 (Print), ISSN 2721-1207 (online)

Table 1. Flood Risk Zoning Classification

Risk Zone Class	**Score Value Range**
Very Low	0 - 1
Low	1.01 - 2
Moderate	2.01 - 3
High	3.01 – 4
Very High	4.01 - 5

Validation was performed using the Kappa test to measure the accuracy of the land change simulation model. The analysis process included the stages of raster data processing, determination of change drivers, analysis of land transition probabilities, and integration of spatial simulation results in an overlay system to obtain detailed flood zoning.



Reference Map: GIS/OtherExamples/Molusce/LU_2022.tif

Simulated Map: IS/OtherExamples/Molusce/sim_result.tif

☑ Validation Map ☑ Check persistent classes

Number of validation iterations: 5

% of Correctness: 88.16742

Kappa (overall): 0.84870

Kappa (histogram): 0.95518

Kappa (location): 0.88853

Figure 4. Kappa Validation

Results and Discussion

Land cover development in the Bolon watershed in 2017, 2021, and 2024

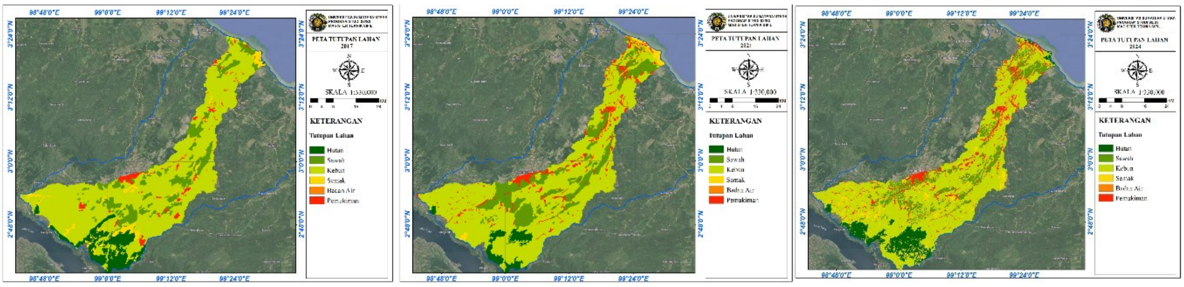


Figure 5. Land Cover Maps for 2017, 2021, and 2024

The results of the study show that between 2017 and 2021, there were significant changes in land cover in the Bolon watershed, with a total of 67.55 km² of forest and agricultural land converted into residential areas. Urbanization was the main factor driving this change, followed by infrastructure growth and local economic activity.

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Land Cover Change Projections

Predictive analysis using the CA–Markov Chain model shows that the trend of land cover change is expected to continue until 2033.

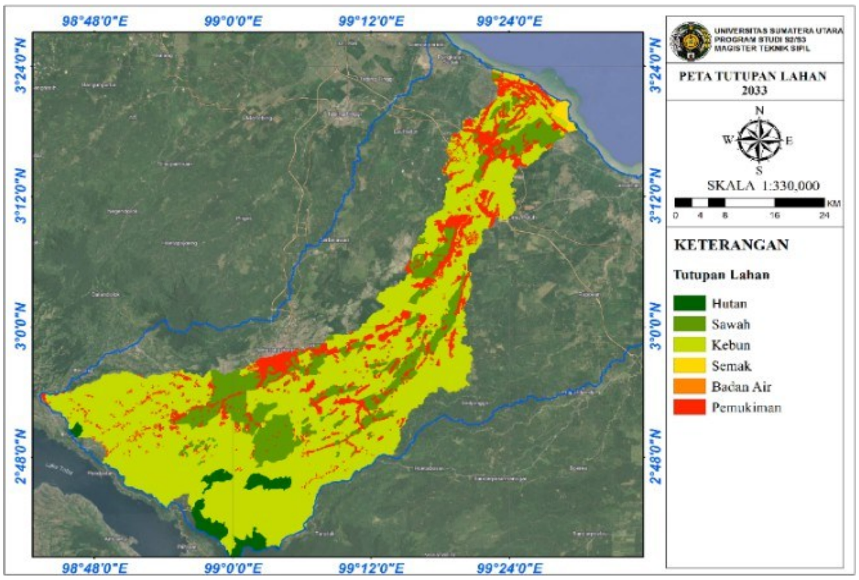
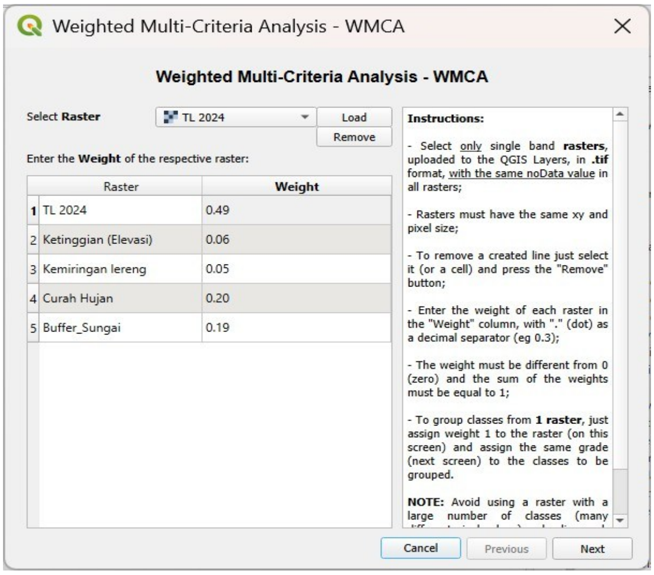


Figure 6. Land Cover Simulation for 2033

Flood Projections on Land Cover

A weighted overlay combining each thematic map with its respective weight produces a map of primary flood vulnerability for the Analytic Hierarchy Process (AHP) and Multi-Influence Factor (MIF) models. The AHP overlay results using WMCA show that high flood risk zones are distributed in lowland areas and areas adjacent to major rivers (Syahputra et al., 2021). Meanwhile, areas with higher elevations and dense vegetation cover show lower risks. This indicates a direct relationship between land use change and increased flood intensity (Epuh et al., 2024; Mustafa et al., 2025; Simangunsong et al., 2024).



Weighted Multi-Criteria Analysis - WMCA

Select **Raster**: TL 2024

Enter the **Weight** of the respective raster:

	Raster	Weight
1	TL 2024	0.49
2	Ketinggian (Elevasi)	0.06
3	Kemiringan lereng	0.05
4	Curah Hujan	0.20
5	Buffer_Sungai	0.19

Instructions:

- Select only single band **rasters**, uploaded to the QGIS Layers, in **.tif** format, with the same noData value in all rasters;

- Rasters must have the same xy and pixel size;

- To remove a created line just select it (or a cell) and press the "Remove" button;

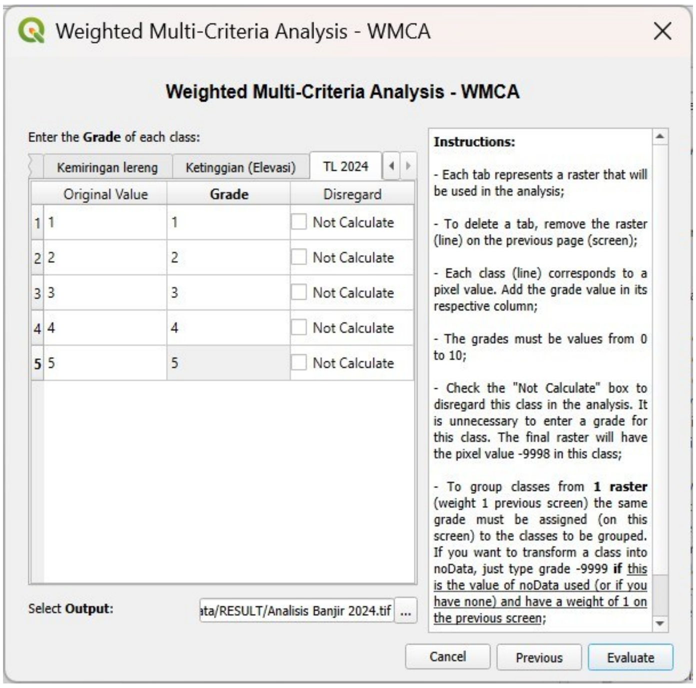
- Enter the weight of each raster in the "Weight" column, with "." (dot) as a decimal separator (eg 0.3);

- The weight must be different from 0 (zero) and the sum of the weights must be equal to 1;

- To group classes from **1 raster**, just assign weight 1 to the raster (on this screen) and assign the same grade (next screen) to the classes to be grouped.

NOTE: Avoid using a raster with a large number of classes (many

Figure 7. Input of flood variable data and weights into WMCA



Weighted Multi-Criteria Analysis - WMCA

Enter the **Grade** of each class:

	Original Value	Grade	Disregard
1	1	1	☐ Not Calculate
2	2	2	☐ Not Calculate
3	3	3	☐ Not Calculate
4	4	4	☐ Not Calculate
5	5	5	☐ Not Calculate

Select **Output**: ata/RESULT/Analisis Banjir 2024.tif

Instructions:

- Each tab represents a raster that will be used in the analysis;

- To delete a tab, remove the raster (line) on the previous page (screen);

- Each class (line) corresponds to a pixel value. Add the grade value in its respective column;

- The grades must be values from 0 to 10;

- Check the "Not Calculate" box to disregard this class in the analysis. It is unnecessary to enter a grade for this class. The final raster will have the pixel value -9998 in this class;

- To group classes from **1 raster** (weight 1 previous screen) the same grade must be assigned (on this screen) to the classes to be grouped. If you want to transform a class into noData, just type grade -9999 **if** this is the value of noData used (or if you have none) and have a weight of 1 on the previous screen;

Figure 8. Input of Scoring Values for Each Flood Variable

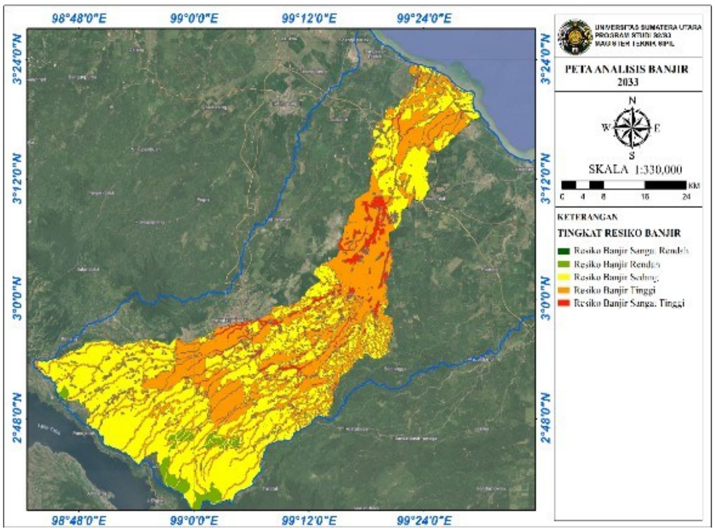
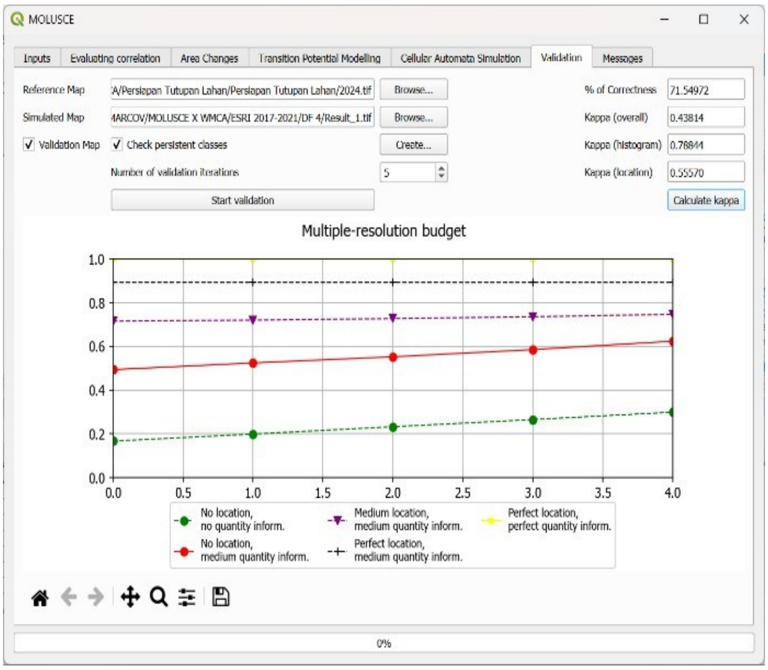


Figure 9. Flood Analysis Map for 2033

After scoring the Rainfall, Slope, Elevation, and Distance from River maps, the process carried out in the WMCA Plugin allows for the integration of complex spatial data to produce informative flood risk zoning maps. Using weights obtained from AHP, this analysis provides a better understanding of the factors contributing to flood risk zoning in the Bolon watershed (Gacu et al., 2022; Gacul et al., 2024). The hazard index is determined based on the matrix method, which assumes that each area has a maximum vulnerability index as the upper limit. With this assumption, it can be seen that the greater the level of vulnerability, the greater the risk that arises (Senapelan, 2016; Sharker et al., 2025).

Model validation using the Kappa test produced an accuracy value of 0.78, indicating a high degree of conformity between the simulation results and actual conditions. This confirms that the CA–MC and AHP–WMCA approaches are effective in predicting changes in land cover and flood risk zoning spatially and temporally.



Reference Map: A/Persiapan Tutupan Lahan/Persiapan Tutupan Lahan/2024.tif

Simulated Map: ARCOV/MOLUSCE X WMCA/ESRI 2017-2021/DF 4/Result_1.tif

☑ Validation Map

☑ Check persistent classes

Number of validation iterations: 5

% of Correctness: 71.54972

Kappa (overall): 0.43814

Kappa (histogram): 0.78844

Kappa (location): 0.55570

Figure 10. Kappa Validation Test Results

The results of the study show that changes in land cover have a direct impact on increasing flood zoning in the Bolon watershed. Land conversion from forest to residential areas has resulted in a reduction in water catchment areas and an increase in surface runoff volume. This condition worsens the region's hydrological system and increases the potential for seasonal flooding in densely populated residential areas. Residential areas with a very high flood risk increased from 1.4% (2017) to 2.89% (2021) and are predicted to reach 4.74% in 2033, with an average increase of 0.21% per year.

Table 2. Flood Zoning in Percent

Flood Risk Percentage (%)

Zoning Level	Score	2017	2021	2024	2025	2029	2033
Very Low	1	0.48	0.47	0.42	0.47	0.42	0.47
Low	2	7.81	3.49	7.56	2.82	2.65	2.51
Moderate	3	55.85	52.39	52.38	51.93	50.83	50.18
Height	4	34.46	40.76	36.95	41.29	41.92	42.10
Very High	5	1.40	2.89	2.69	3.49	4.18	4.74
		100	100	100	100	100	100

The correlation results between settlement and flood risk zoning for the period 2017 to 2033 show that uncontrolled settlement development and land conversion from undeveloped to developed land contribute significantly to increased flood risk. Increased settlement causes a decrease in soil infiltration rates, thereby accelerating and increasing surface water runoff that triggers flooding.

ISSN 2721-1304 (Print), ISSN 2721-1207 (online)

Table 3. Correlation Results for the Relationship Between Settlements and Very High Flood Zoning from 2017 to 2033

Year	**Settlements (km^2)**	**Very High Flood Zone (km^2)**
2017	58.51	26.96
2021	126.06	55.55
2024	151.68	51.57
2025	167.047459	67.04
2029	217.57146	80.24
2033	252.46882	91.01

Settlements around the Bolon watershed are increasingly vulnerable to flooding due to changes in flood hazard zoning triggered by deforestation and land cover changes. The following are the percentages of very high flood zoning areas in the Bolon watershed settlements:

In 2017, the area of flood zoning was 1.4%

In 2021, the area of flood zoning was 2.89%

In 2024, the area of flood zoning was 2.69%

In 2025, the area of high-risk flood zoning was 3.49%

In 2029, the area of flood zoning was 4.18%

In 2033, the area of flood zoning was 4.74%

The average increase in the percentage of flood zone area is around 0.21% per year during the period 2017 to 2033. Previous research in the Gidabo sub-watershed in Ethiopia showed that the response of river discharge to LULC changes indicated that the average annual river flood discharge increased by 2.13% (1.16 million3/s) and 3.62% (2.04 million3/s) during the periods 1990–2005 and 2005–2019, respectively due to LULC changes (Serur and Adi, 2022).

By performing regression calculations, the equation shown in the graph was obtained. A value close to 1 indicates that the model fits the data very well and shows that there is a very strong positive correlation between the area/level of settlement and flood risk. This means that the higher the settlement value, the higher the flood risk in the data.

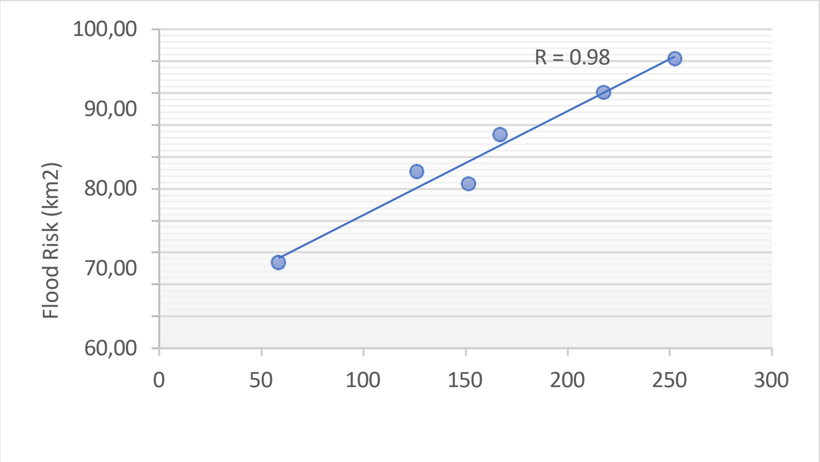


Figure 11. Graph of Correlation Results for the Relationship between Settlement and Flood Risk Zoning from 2017 to 2033

ISSN 2721-1304 (Print), ISSN 2721-1207 (online)

During the period 2017–2033, there was a significant increase in the percentage of very high hazard flood zones. The sharpest increase occurred between 2017 and 2021. After that, although there was a slight decrease in the very high hazard flood zone in 2024 due to a 4.6% increase in forest area, this increase in the very high hazard flood zone is likely related to other

land cover changes, such as a decrease in forest and plantation area and an increase in settlement area. These changes can lead to a reduction in water absorption and an increase in surface runoff, thereby enlarging the flood zone in the region. Thus, the extremely high-risk flood zone shows a consistent upward trend, requiring special attention in spatial planning and flood zone mitigation efforts in the future (Dwarakish et al., 2024; Fauzi, 2022; Azadgar et al., 2024; Meng et al., 2022; Wang et al., 2022; Ding et al., 2022).

These findings are consistent with the research by Supriatna et al. (2022), which states that more than 70% of flooding events in Indonesia are caused by land use changes. Furthermore, according to Shadmaan & Hassan (2024), urbanization without sustainable planning is a dominant factor causing increased hydrological risk in tropical regions (Shadmaan & Hassan, 2024; Supriatna et al., 2022).

The implementation of the AHP–WMCA method provides relevant results because it is able to integrate quantitative and qualitative data in determining the priority of flood-causing factors. This method assists in evidence-based decision-making for risk mitigation. Thus, the results of this study can be a reference for local governments in disaster risk-based spatial planning.

From a spatial perspective, areas located in lowlands and near rivers require special attention through the strengthening of drainage infrastructure and vegetation conservation. Regular monitoring of land cover using GIS technology is an important step in controlling inappropriate land use change. Overall, this study emphasizes the need for spatial planning policies that are adaptive to environmental changes and disaster risk mitigation. The predictive model-based geospatial approach provides scientific solutions that can be used to support sustainable development in the Bolon watershed and surrounding areas.

Conclusion

Based on the results of the analysis of the impact of land cover change on flood hazard zoning in residential areas in the Bolon watershed, with increased runoff, areas that were previously classified as low or moderate risk are now classified as high and very high flood hazard zones ( ), including residential areas around the Bolon watershed. Settlements around the Bolon River Basin are increasingly vulnerable to flooding due to changes in flood hazard zoning triggered by deforestation and land cover changes. The projected percentage of areas with very high flood hazard zoning in residential areas of the Bolon River Basin in 2033 is 4.74%, with an average increase in the percentage of areas with high flood hazard zoning of around 0.21% per year during the period 2017 to 2033.

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