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GIS-based Flood Susceptibility Prediction using Google Earth Engine in Halmahera Tengah Regency, Indonesia

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Abstract. Flooding is a recurring hydrometeorological hazard in Halmahera Tengah Regency, North Maluku, causing environmental and socio-economic losses and highlighting the need for effective mitigation. This study aimed to develop a flood susceptibility map for the regency, which has lacked spatially based flood assessments despite frequent flood events. The analysis used a Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) processed on Google Earth Engine, with five controlling variables: distance from permanent water bodies, elevation, Topographic Position Index (TPI), NDVI, and NDWI. The results show that Halmahera Tengah is dominated by moderate flood susceptibility, covering 125,458.40 ha or 56.40% of the area. High susceptibility covers 62,087.25 ha (27.91%), while low susceptibility covers 34,900.10 ha (15.69%). At the subdistrict level, flood susceptibility is unevenly distributed, with Weda Tengah, Weda Timur, and Weda Utara containing extensive moderate to high-risk zones. Model validation using ROC produced an AUC value of 0.827, indicating good model performance. The findings also align with the Sustainable Development Goals, particularly SDG 13.1 on climate and disaster resilience, SDG 11.5 on reducing disaster impacts, and SDG 15.3 on land degradation and land cover management. Overall, the study shows that flood susceptibility mapping can support spatial planning, improve disaster preparedness, and strengthen future flood risk reduction efforts in Halmahera Tengah Regency.

***Keywords:** Flood; Halmahera Tengah; GIS; MCDA; Google Earth Engine*

1. Introduction

Flooding is one of the most frequent natural disasters and causes highly detrimental impacts in social, economic, and environmental terms across many countries, especially developing countries such as Indonesia (BNPB, 2025; Pertuack et al., 2026). Data from the National Disaster Management Agency (BNPB) show that throughout 2024, Indonesia recorded 2,107 disaster events, 1,088 of which were floods, causing 547 deaths, more than 6.3 million evacuees, and about 60,000 damaged houses (BNPB, 2025). Global climate change has increased the intensity of extreme rainfall and has made flooding more frequent and severe, especially in tropical regions of Southeast Asia. Therefore, flood susceptibility mapping is very important as a disaster risk reduction instrument, enabling governments and communities to identify high-risk areas, develop early warning systems, and formulate effective mitigation strategies (Ravi Chandra et al., 2024).

Halmahera Tengah Regency in North Maluku Province has a very high vulnerability to flooding due to a combination of geographic characteristics, high rainfall intensity, and increasing anthropogenic pressure (BNPB, 2025). In the past five years, this area has experienced several major flood events that caused significant losses, including the flood on

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7 August 2023 that affected Messa Village and Kotalo Village in East Weda District, as well as the July 2024 flood that inundated four villages in Central Weda District to a depth of 2 meters after the Kobe River overflowed, forcing thousands of residents to evacuate and carrying mining materials that polluted the environment (Priambodo & Kamis, 2022; Rakuasa & Khromykh, 2026). These flood events were caused not only by climatological factors but also worsened by massive deforestation and intensive nickel mining activities that have damaged environmental carrying capacity and altered the natural hydrological system (Kamis & Priambodo, 2022). The North Maluku branch of the Indonesian Forum for the Environment (WALHI) stated that the loss of forest cover, which functions as a water catchment area, the degradation of riparian ecosystems, and river sedimentation caused by mining waste have made rivers such as Kobe, Akejira, Saloi, Kluting, Kesayangan, and Jodoh easily overflow during heavy rainfall (Jaya et al., 2024; (Fiqri, & Azwar 2024).

Geographic Information System (GIS) technology integrated with machine learning algorithms has proven to be a highly effective approach for mapping flood susceptibility with a high level of accuracy (Aizemu & Rakuasa, 2026). Studies in various regions of Indonesia, such as West Java, East Java, Central Sulawesi, and Barru Regency, have successfully applied GIS-based methods to identify flood-prone zones by utilizing various conditioning factors such as elevation, slope, land use, rainfall, distance from rivers, the Topographic Wetness Index (TWI), and the Stream Power Index (SPI) (Sugandhi & Rakuasa, 2023; Irawan et al., 2023; Raghava & Viswanadh, 2025)

Google Earth Engine (GEE) has revolutionized the field of geospatial analysis by providing a cloud computing platform with the capacity to process satellite data at planetary scale (Khoeun et al., 2022; Rakuasa et al., 2024). The platform provides free access to more than 80 petabytes of satellite imagery from various sensors such as Landsat, Sentinel, MODIS, and other continuously updated environmental data sources, covering a period of more than 50 years. The main advantage of GEE is its ability to reduce analyses that would take weeks on a local computer to only a few minutes, making it highly ideal for large-scale environmental monitoring and disaster risk assessment (Deopa & Resmi, 2025). In Indonesia, GEE has been applied to various environmental studies, including mapping flooded areas using Sentinel-1 SAR data, monitoring land cover change, and analyzing coastal vulnerability (Sholeh et al., 2025).

Based on the sustainable development goals to create a better future in 2030, there is a correlation between the agenda and research that is very relevant to SDG 13.1, that strengthening adaptation to climate hazards and disasters that focus on strengthening resilience and adaptive capacity to climate-related hazards and natural disasters, so that the GEE-based flood prediction model can be an instrument for measuring parameters for climate adaptation. While SDG 11.5 has a relationship because it supports reducing the impact of disasters on humans and impacts on the economy, the results of the flood vulnerability map in this study can be used for spatial planning, preparedness or mitigation, and risk reduction in affected areas as well as a relevant correlation of this study with SDG 15.3 because flood disasters have a relationship with land degradation, land cover changes, deforestation, and decreased watershed function (Sholeh et all., 2025)

Although research on flood susceptibility has been widely conducted in various regions of Indonesia, studies specifically focused on Halmahera Tengah Regency are still lacking, creating a significant knowledge gap in understanding the spatial pattern of flood susceptibility in this area. This study aims to develop a GIS-based flood susceptibility prediction model for Halmahera Tengah Regency using the cloud computing capabilities of Google Earth Engine and a multi-criteria decision analysis (MCDA) approach. By utilizing multi-source satellite data, topographic variables, hydrological factors, and vegetation indicators, this research is expected to produce a high-resolution flood susceptibility map that identifies the spatial pattern of flood risk and provides actionable insights for local governments, disaster management agencies, and communities to implement effective mitigation measures and adaptive early warning systems. The contribution of this research is that it can help identify priority areas for flood management, support mitigation and preparedness, and add to regional disaster data.

2. Methods

2.1. Study Location and Data

This study was conducted in Halmahera Tengah Regency, North Maluku, Indonesia, a region chosen because of its high flood vulnerability and the lack of previous flood-hazard modeling studies there. The study area (ROI) was defined using administrative boundaries and used as the clipping extent for all imagery and elevation products. Primary data include the JRC Global Surface Water (GSW) v1.4 product to detect permanent water (occurrence > 80%), the SRTM DEM (30 m) for elevation, and Landsat 8 Collection 2 Surface Reflectance imagery from 2026 to compute NDVI and NDWI. The use of the GSWO product to identify permanent water has been globally validated and proven effective for flood mapping in various regions.

2.2. Data Processing and Analysis

Preprocessing was carried out entirely in Google Earth Engine (GEE), a cloud-computing platform that enables efficient large-scale spatial analysis. Landsat 8 imagery was filtered by the ROI boundary, and a cloud-masking function using the QA_PIXEL band (bitmask for clouds, cirrus, and shadows) was applied to produce a cloud-free median composite. The SRTM DEM and the water maps were clipped to the ROI and reprojected to EPSG:4326 with a 30 m resolution for analysis consistency. This approach aligns with previous studies that used GEE for automated flood mapping and impacted-area inventories.

2.2.2. Multi-Criteria Decision Analysis (MCDA)

This study used the Multi-Criteria Decision Analysis (MCDA) method, implemented by summing scored layers of environmental variables (Distance, Elevation, TPI, NDVI, NDWI) to form a flood-hazard index. Each variable was scored into five classes (1–5) based on empirical thresholds and expert judgment, then summed with equal weights. This simple weighted-sum method (Table 1) has been applied in various GIS- and GEE-based flood-vulnerability studies. Fernandez et al., (2023), demonstrated that integrating MCDA with environmental factors in GEE can produce accurate flood-susceptibility maps with AUC > 0.95.

Table 1. Flood Vulnerability Parameters and Scores

Parameter	Class/Range	Score	Susceptibility Level
Distance from Permanent Water (m)	< 1000	5	Very High
	1000 - 2000	4	High
	2000 - 3000	3	Medium
	3000 - 4000	2	Low
	> 4000	1	Very Low
Elevasi (m)	0- 5	5	Very High
	5-10	4	High
	10-15	3	Medium
	15-20	2	Low
	>20	1	Very Low
Topographic Position Index (TPI)	< -8	5	Very High
	-8 to -6	4	High
	-6 to -4	3	Medium
	-4 to -2	2	Low
	> -2	1	Very Low
NDVI	-1.0 – 0.0	5	Very High
	0.0 – 0.2	4	High
	0.2 – 0.4	3	Medium
	0.4 – 0.6	2	Low
	0.6 – 1.0	1	Very Low
NDWI	> 0.6	5	Very High
	0.2 - 0.6	4	High
	-0.2 - 0.2	3	Medium
	-0.6 - (-0.2)	2	Low
	< -0.6	1	Very Low

Source: (Fernandez et al., 2023; Diriba et al., 2024; Rifai et al., 2025)

2.2.3. Processing Environmental Variables

Five environmental variables were processed as flood-controlling factors. Distance from Permanent Water was derived from the GSWO map (occurrence > 80%) using a fastDistanceTransform to convert pixel distance to meters; proximity to permanent water significantly increases flood risk. Elevation was taken from SRTM and classified by ranges (>20 m to ≤5 m) because low elevation strongly correlates with flood vulnerability due to natural water flow. The Topographic Position Index (TPI) was calculated as the difference between a cell's elevation and the mean elevation of its neighbors (focalMean of 5 cells) to identify valleys (negative TPI) and ridges (positive TPI); TPI has been shown to be an important predictor of flooding. NDVI was computed from Landsat 8 (NIR and RED) using the formula NDVI = (NIR − RED) / (NIR + RED) to assess vegetation cover, where high NDVI indicates dense vegetation that reduces flood risk. NDWI was calculated from GREEN and NIR using the formula NDWI = (GREEN − NIR) / (GREEN + NIR) to measure surface wetness, with high NDWI correlating with wet or inundated areas. There are Flood vulnerability variables that we used; Distance from permanent water bodies, Elevation, Topographic Position Index (TPI), NDVI, and NDWI (Figure 1).

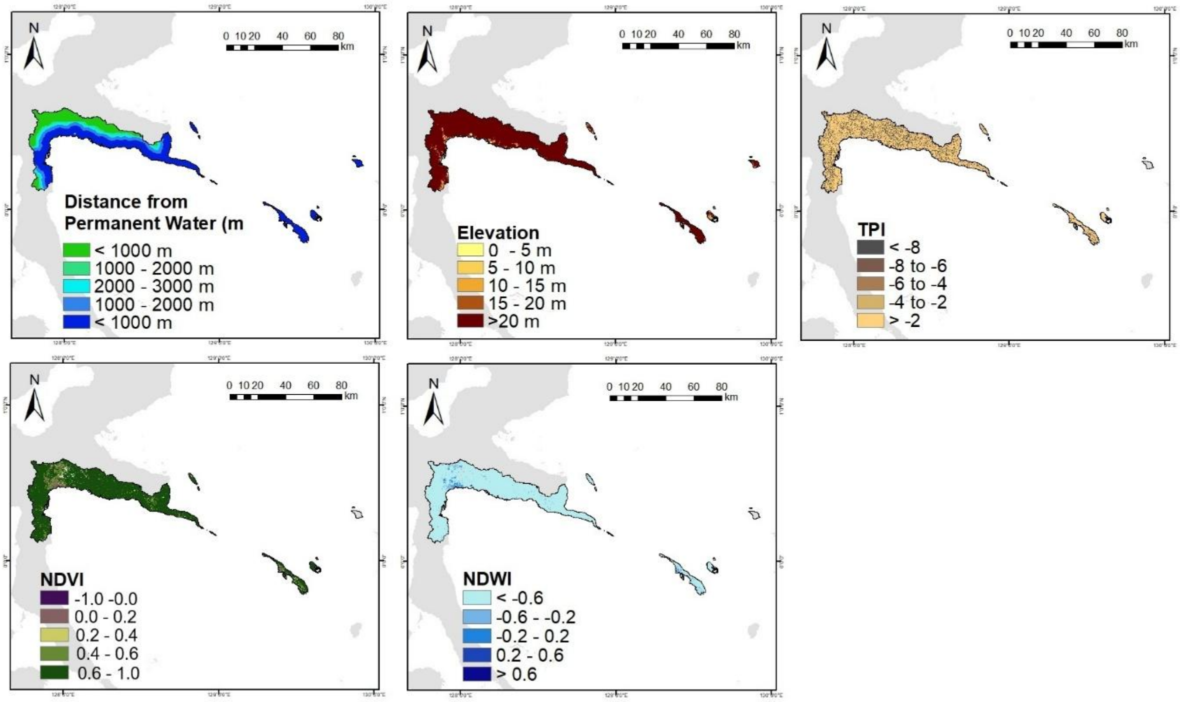

Figure 1. Flood vulnerability variables

2.2.4. Flood Hazard Classification

The resulting flood-hazard index, produced by summing the five scored variables, was classified into three classes low, medium, and high using a quartile-based approach combined with expert judgment. This three-class scheme effectively distinguishes areas of minimal, moderate, and maximal risk, following GEE-based flood-susceptibility practices that simplify map interpretation for planners. Thresholds were chosen based on the index value distribution, and the final map was exported at a 10 m scale for documentation and further analysis.

2.2.5. Model Validation

Model validation was performed by comparing the susceptibility map against an inventory of flood events (point/polygon records of historical floods or field observations). The dataset was split into 70% for training and 30% for validation, following standard practice in machine-learning flood modelling. Statistical metrics such as accuracy, sensitivity, specificity, F1-score, and Kappa were calculated to assess classification performance (Javidan et al., 2021).

Model performance was evaluated using the Receiver Operating Characteristic (ROC) curve and the Area Under the Curve (AUC). The ROC plots the true positive rate against the false positive rate across different thresholds, while the AUC provides an aggregate measure of the model's discriminative ability. AUC > 0.9 indicates excellent performance, whereas AUC ≈ 0.5 indicates random performance. The ROC–AUC method is the most common technique for validating flood-susceptibility models and has been widely used in previous studies.

3. Results and Discussion

3.1. Flood susceptibility of Halmahera Tengah Regency

Based on the MCDA modeling results, Halmahera Tengah Regency is dominated by the moderate flood susceptibility class, covering 125,458.40 ha (56.40%), followed by the high class covering 62,087.25 ha (27.91%), and the low class covering 34,900.10 ha (15.69%). This finding indicates that more than half of the region has the potential to experience inundation during intense rainfall events, meaning that flood susceptibility in this area is not only localized but also spatially extensive (Figure 2).

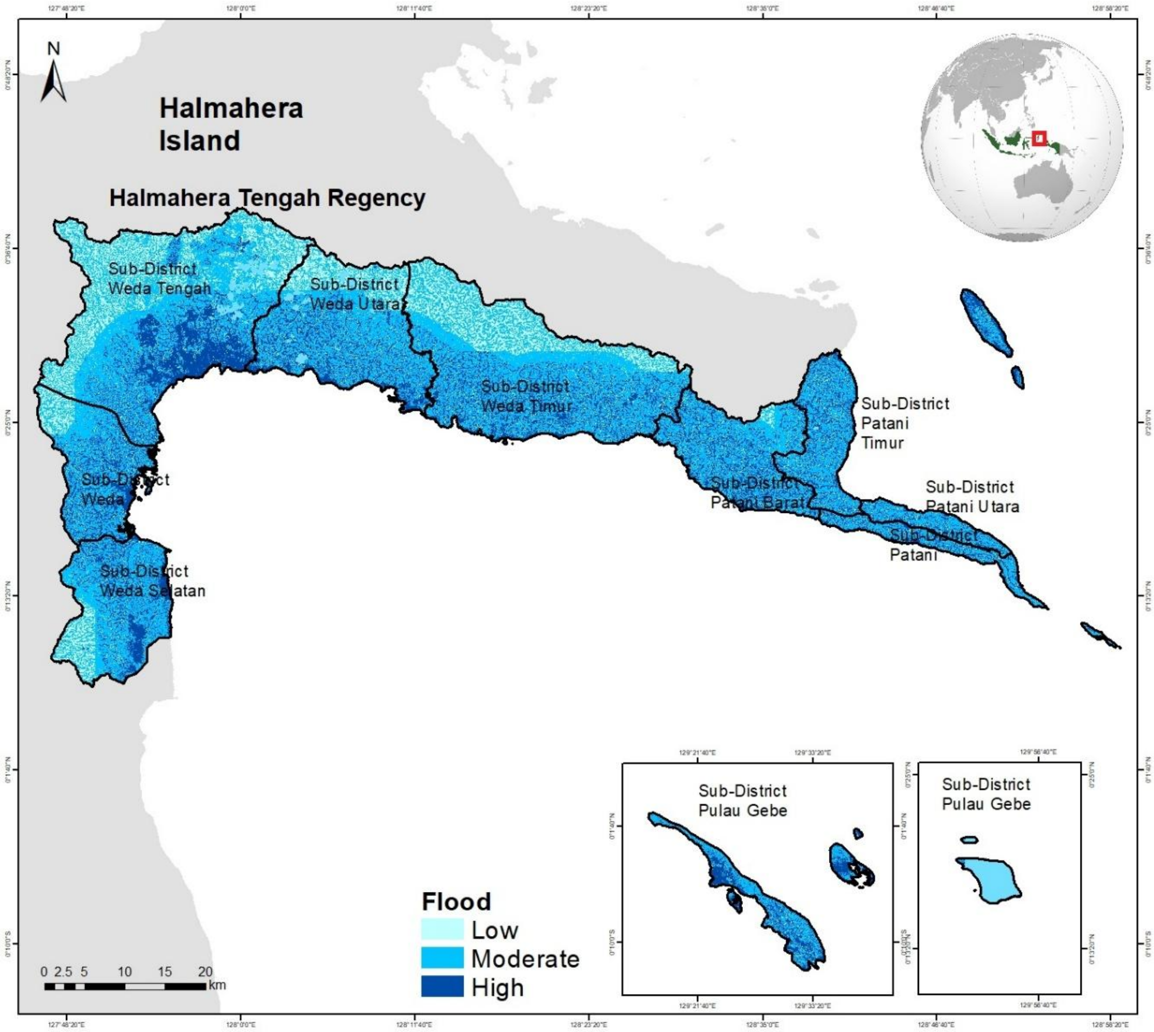

Figure 2. Flood susceptibility of Halmahera Tengah Regency

Spatially, these results are likely influenced by the combination of variables including distance from permanent water bodies, elevation, Topographic Position Index (TPI), NDVI, and NDWI. Areas close to rivers or permanent water bodies, located at low elevations, and occupying concave topographic positions generally more easily accumulate surface runoff and water, while low NDVI values may indicate sparse vegetation cover, reducing infiltration and increasing runoff; meanwhile, NDWI helps identify wetter surfaces and is often associated with inundated areas or proximity to water (Javidan et al., 2021). Therefore, the dominance of moderate and high classes in Halmahera Tengah suggests that spatial planning and flood mitigation should be prioritized in low-lying zones, areas near waterways, and sparsely vegetated regions.

3.2. Flood Susceptibility Level by Subdistrict

Sub-district-level analysis shows that flood susceptibility in Halmahera Tengah is spatially varied, with the moderate class dominating in most sub-districts. Weda Tengah has the largest area in the moderate class at 28,047.74 ha, followed by Weda Timur at 27,349.06 ha and Weda Utara at 15,517.62 ha, indicating that these areas are broadly exposed to flood-related conditions. In contrast, the low class is relatively smaller in most sub-districts, although Weda Tengah still records the largest low-susceptibility area at 13,159.89 ha, suggesting a mixed spatial pattern rather than uniform flood conditions across the regency.

The high susceptibility class is also significant in several sub-districts, especially Weda Timur (9,775.88 ha), Pulau Gebe (8,308.91 ha), and Weda Utara (7,505.86 ha). This pattern suggests that certain sub-districts contain more vulnerable terrain, likely due to combinations of low elevation, proximity to permanent water bodies, concave topography, and limited vegetation cover. Such characteristics are commonly associated with greater runoff accumulation and reduced drainage efficiency, which increase flood susceptibility in MCDA-based flood mapping studies.

Table 2. Flood Susceptibility Level by Subdistrict

Sub-District	Flood susceptibility classes		
	Low	Moderate	High
Weda	1.961,62	9.352,44	5.056,52
Patani	327,28	3.145,11	2.125,78
Pulau Gebe	572,74	8.652,97	8.308,91
Weda Utara	4.474,12	15.517,62	7.505,86
Weda Selatan	2.512,89	11.778,89	5.512,51
Patani Utara	224,79	2.545,88	1.391,79
Weda Tengah	13.159,89	28.047,74	11.085,88
Patani Barat	1.314,42	11.125,16	5.922,29
Weda Timur	9.607,46	27.349,06	9.775,88
Patani Timur	736,01	7.933,33	5.370,46

Overall, the results indicate that flood mitigation in Halmahera Tengah should be prioritized in sub-districts with large moderate-to-high susceptibility areas, particularly Weda Tengah, Weda Timur, Weda Utara, Weda Selatan, and Pulau Gebe (Table 2). These findings are consistent with GIS-based flood susceptibility research showing that areas close to water bodies, with low elevation and sparse vegetation, tend to experience higher flood vulnerability (Al Kuisi et al., 2024). Therefore, spatial planning, drainage improvement, land-use control, and watershed-based management should be focused on these high-risk sub-districts to reduce future flood impacts (Dar et al., 2025).

3.3. Model Validation

The validation model using the Receiver Operating Characteristic (ROC) curve shows that the flood susceptibility model on Halmahera Tengah has quite satisfactory performance on the training data with an AUC value of 0.827, which is generally categorized as "good" or "excellent" in machine learning-based flood susceptibility modeling (Huang et al., 2024). This value is comparable to various flood susceptibility studies in Indonesia and globally, which state that an AUC ≥ 0.8 indicates strong prediction accuracy between flooded and non-flooded pixels. Several flood susceptibility mapping studies report an AUC of around 0.83–0.90 as very adequate performance for risk management and spatial planning applications, thus placing the Halmahera Tengah model within an acceptable range for practical applications. The model validation results can be seen in Figure 3.

However, the model's performance on the test data decreased to an AUC of 0.673, which is only slightly higher than random prediction (AUC 0.5), indicating signs of overfitting and limitations in the model's generalization ability when faced with unseen data (Kalita et al., 2025). In the literature, an AUC of around 0.65–0.70 is generally classified as "moderate" or "fair" accuracy, still usable for initial susceptibility mapping but not ideal for very critical decisions without additional calibration. Thus, the Halmahera Tengah flood susceptibility model can be used in principle, but it is more appropriately positioned as a decision support tool (screening tool) and for prioritizing vulnerable areas, while recommending improvements in flood inventory quality, balancing training-testing data, and exploring additional algorithms or parameter tuning to increase the AUC on test data above the 0.75 range to make it more reliable for long-term structural and non-structural policies. The model validation results can be seen in Figure 3.

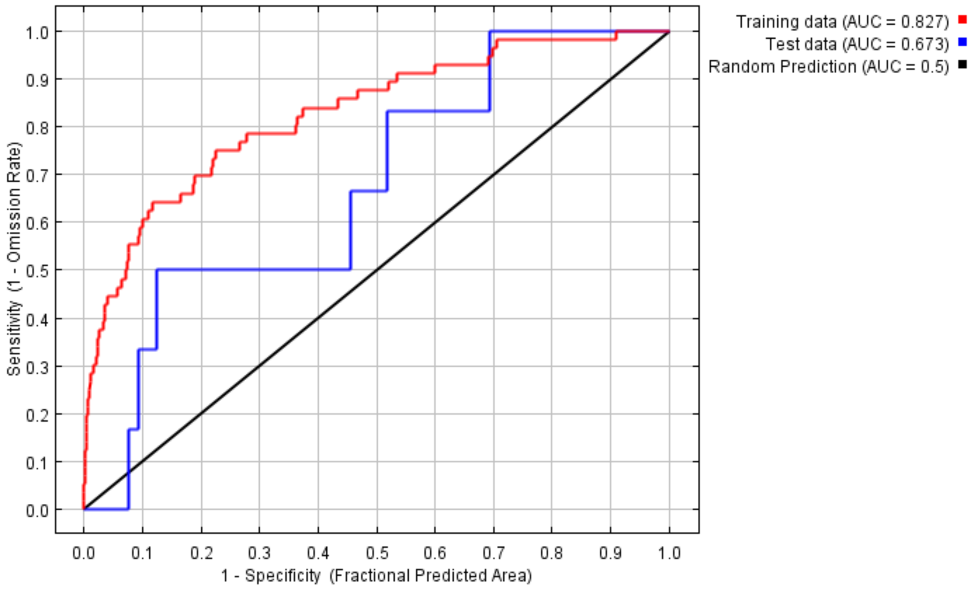

Figure. 3. Flood Model Receiver Operating Characteristic (ROC) Curve.

3.4. Recommendations for future flood disaster mitigation

In the future, flood mitigation strategies in Halmahera Tengah Regency should be directed toward the comprehensive integration of structural and non-structural approaches. On the structural side, the main priorities should include river normalization, drainage capacity improvement, construction of runoff control channels, and watershed conservation through the rehabilitation of vegetation cover in upstream areas and low-elevation zones. This approach is particularly important because the modeling results indicate that a substantial portion of the region falls within the moderate to high flood susceptibility classes, making runoff management and infiltration enhancement essential requirements for reducing the potential for surface inundation and overbank flooding (Rakuasa & Rifai, 2025). Such physical interventions should therefore be spatially targeted toward areas adjacent to permanent water bodies, concave topographic settings, and land cover with relatively low vegetation density (Rakuasa et al., 2022; Nouhou et al., 2025).

Meanwhile, from a non-structural perspective, mitigation efforts should be strengthened through the integration of flood susceptibility maps into spatial planning policies, land-use control in vulnerable areas, and the development of early warning systems based on hydrometeorological parameters (Chukwu et al., 2023). The local government should also enhance community capacity through disaster education, evacuation drills, and the establishment of community-based disaster preparedness institutions at the village and subdistrict levels (Diriba et al., 2024). From an academic standpoint, this approach aligns with the principles of landscape-based disaster risk reduction, which recognize that flood vulnerability is determined not only by physical conditions, but also by spatial governance, social preparedness, and the quality of coordination among stakeholders. Accordingly, flood mitigation in Halmahera Tengah should be positioned as a cross-sectoral agenda that combines technical control, spatial policy, and community empowerment.

Conclusions

This study shows that Halmahera Tengah Regency is dominated by moderate to high flood susceptibility, with spatial variation across subdistricts influenced by physical factors such as distance from permanent water bodies, elevation, TPI, NDVI, and NDWI. Model validation indicates good performance on the training data, but a decline on the testing data, suggesting that the model is more appropriately used as a decision-support tool for identifying priority mitigation zones. Accordingly, the findings emphasize the need to integrate flood susceptibility maps into spatial planning, strengthen drainage systems and watershed conservation, and improve community preparedness through targeted structural and non-structural mitigation approaches based on spatial analysis.

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Conflicts of Interest

The authors declare no conflict of interest

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