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RESEARCH ARTICLE

Optimizing Tsunami Evacuation Route with GIS and Network Analysis: Case Study of Barus City, Central Tapanuli, Indonesia

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Abstract

A tsunami is a natural disaster triggered by the vertical displacement of the seafloor following a major earthquake along a megathrust zone. Barus District lies within the active Sumatran megathrust, making it highly vulnerable to large earthquakes that could generate tsunamis. This study aims to map tsunami hazard and risk zones under a 16-meter wave scenario and to model evacuation routes using Geographic Information Systems (GIS) and Remote Sensing approaches. The research employs a descriptive quantitative method, integrating spatial data through overlay and network analysis techniques. The analysis revealed that high-hazard and high-risk zones each cover 0.64 km^2 out of the total 2.27 km^2, primarily located in Pasar Terandam and Pasar Batu Gerigis villages. Evacuation route modeling showed estimated travel times ranging from 25.06 to 65.73 minutes, assuming an average walking speed of 1.2 m/s. Among the designated shelters, the Catholic church offers a more efficient route, whereas evacuation to the HKBP church requires more than 60 minutes exceeding the ideal time limit. These findings highlight the urgent need to prioritize disaster mitigation strategies to ensure the effectiveness of tsunami evacuation systems in high-risk coastal areas.

Keywords: Network Analysis, Tsunami, Geographic Information System (GIS), Remote Sesing, Evacuation Routes

1. Introduction

Barus District is a coastal area on the western side of Central Tapanuli Regency, North Sumatra Province. It directly borders the Indian Ocean and lies within the active subduction zone where the Indo-Australian Plate converges beneath the Eurasian Plate (Ginting et al., 2023). Seismic activity studies indicate a high level of seismic intensity in the area, with thousands of earthquakes recorded during the 2020–2021 period, posing a potential risk of triggering tsunamis (Lubis et al., 2022).

A tsunami occurs as a result of the sudden vertical displacement of the seafloor, typically caused by a major undersea earthquake along a megathrust zone (Wijanarko et al., 2022). Barus District lies within the tectonically active Sumatran megathrust zone, making it highly vulnerable to earthquakes of up to magnitude 9 Mw, which could potentially trigger tsunamis reaching heights of up to 30 meters (Subarya et al., 2006).

This potential risk is further reinforced by the topographic characteristics of Barus District, which is relatively flat with elevations ranging from 0 to 8 meters above sea level and its close proximity to the coastline factors that significantly heighten tsunami risk. In addition, the high population density of 853.99 people per km^2 increases the community's social vulnerability in facing such disasters (Badan Pusat Stastistik Kabupaten Tapanuli Tengah, 2023).

As part of disaster mitigation efforts, a worst-case scenario approach was applied by modeling a tsunami wave height of 16 meters (Fathianpour et al., 2023). This approach was chosen to project the maximum possible impact, drawing on the 2004 Aceh tsunami, which generated waves exceeding 15 meters and claimed 129,775 lives. Planning mitigation measures based on such extreme scenarios is crucial to ensure that evacuation systems can continue to function effectively under disaster conditions (Ramalanjaona, 2011).

This condition is compounded by the nature of local tsunamis in Indonesia, which generally arrive in less than 45 minutes (Rao, 2006). This fact underscores the need for fast and secure evacuation routes in disaster mitigation planning. In this context, Geographic Information Systems (GIS) and Remote Sensing technologies play a vital role in supporting spatially based evacuation planning. One effective approach is the Network Analysis method, which can identify the fastest and safest evacuation routes to designated shelters by analyzing road networks, travel distances, and potential obstacles (Nurhasanah et al., 2020). The selection of this method is further supported by a previous study (Anggarwati et al., 2023) , which demonstrated that network analysis is more effective in identifying safe routes compared to the Least Cost Distance (LCD) method, which often produces evacuation paths that cross rugged terrain.

This method has been successfully applied in evacuation route modeling in several regions, such as in Palu City (Putra and Chernovita, 2020), Surabaya (Watik and Jaelani, 2019), and in another study (León et al., 2022), all of which produced safe and efficient evacuation routes. However, to date, such modeling has not been conducted in Barus District, despite its high level of tsunami vulnerability and the absence of spatial data–based evacuation systems or structured mitigation planning.

Based on these conditions, this study aims to map tsunami hazard zones in Barus District under a 16-meter tsunami scenario, analyze population risk levels by considering spatial distribution and social vulnerability, and model tsunami evacuation routes from Temporary Evacuation Point (TEP) to Final Evacuation (FEP) in Barus District using a GIS-based approach and the network analysis method.

2. Data and Methods

2. 1 Study Area

Geographically, Barus District in Central Tapanuli Regency is located at 02°02'05"–02°09'29" N and 98°17'18"–98°23'28" E, along the western coast of Sumatra. With a 200 km-long shoreline situated within the seismically active megathrust zone, the area is highly prone to major earthquakes and tsunamis. Barus is also the smallest district in Central Tapanuli, covering an area of 21.81 km^2 and comprising 11 villages and 2 sub districts (Rapson Okardo Purba, 2020).

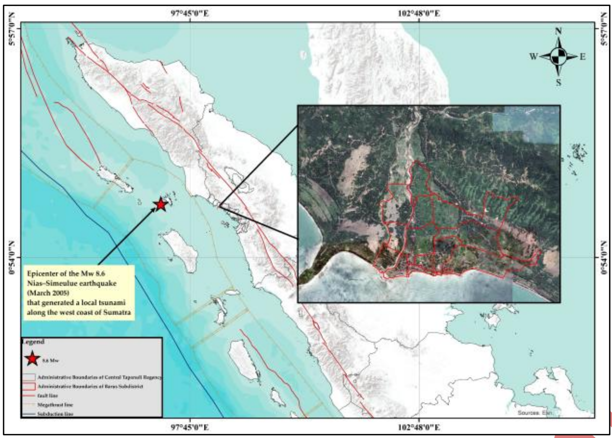

Fig.1 Map of the megathrust zone in western Indonesia showing the Mw 8.6 Nias–Simeulue earthquake epicenter (March 2005) that triggered a local tsunami, with an inset highlighting the coastal area and administrative boundaries of Barus District (Source: Data Processing, 2025)

2. 2 Data and Software

The data used in this study include SAS Planet satellite imagery to obtain land cover information; a 7.5-meter resolution Digital Elevation Model (DEM) from Ina-Geoportal to analyze elevation and slope; Indonesian Topographic Map (RBI) data from the Geospatial Information Agency to gather administrative boundaries of Barus District and road network data; village-level population data from the Central Tapanuli Regency Statistics Office for social vulnerability analysis; and coastline data for cumulative cost analysis of tsunami inundation spread.

Data processing and analysis were carried out using ArcGIS Map version 10.8 for spatial analysis, Google Earth Pro version 7.3.6 for visual interpretation and validation, and Microsoft Excel 2021 for data processing.

2. 4 Processing Data

Spatial data processing was carried out using ArcGIS Map 10.8. Satellite imagery from SAS Planet was manually digitized through a remote sensing approach integrated with GIS to obtain detailed land cover data. The accuracy of the digitization was validated by comparing it with Indonesian Topographic Map (ITM) data. These results were then used to assign roughness coefficient values as parameters in modeling tsunami inundation in Barus District. The roughness coefficient is essential for estimating the extent of tsunami inundation under the 16-meter scenario. Each land cover class was assigned a roughness coefficient value, as shown in Table 1.

Table 1. Roughness Coefficient Value of Land Use

Types of Land Use	Roughness Coefficient
Shrubs / Bushland	0,040
Forest	0,070
Settlement / Residential Area	0,045
Rice Field	0,020
Plantation	0,035
Field / Dryland Farming	0,030
Building / Structure	0,050
Water Body	0,007
Sand / Sand Dunes	0.018
Mixed Crops / Mixed Gardens	0.035
Coastal Shoal / Lagoon	0.015

Source: Berryman, 2006

The processed land cover data of Barus District was assigned roughness coefficient values for each land cover type, as presented in Table 1. The assignment of these coefficient values was carried out using the field calculator tool, which enabled the inclusion of roughness coefficients for each land cover class within the district.

Additionally, a Digital Elevation Model (DEM) with a resolution of 7.5 meters was analyzed using the slope tool in ArcGIS to generate a slope map. This map illustrates the degree of terrain inclination and helps assess the potential extent of tsunami inundation in relation to the area's topographic conditions, referring to the classification outlined in Table 2.

Table 2. Slope Gradient Classification

Slope Class	Slope (%)	Description
1	0 – 8 %	Flat
2	8 – 15 %	Gentle
3	15 – 25 %	Moderately Steep
4	25 – 45 %	Steep
5	45% or more	Very Steep

Source: Pertanian, 1981

The slope data of Barus District was classified according to Table 2 using the Reclassify tool in ArcGIS to obtain slope class values for the tsunami inundation modeling. Population data were

analyzed spatially through the overlay method using the Field Calculator feature in ArcGIS. The demographic data, consisting of the number of male and female residents, were assigned weights and indicator scores as shown in Table 3

Table 3. Variable Weights, Social Vulnerability Index Scores, and Social Vulnerability Level Classification

Parameter	Weight (%)	Class			Score
		Low	Medium	High	
Population Density	60	< 5 Jiwa/Ha	5 - 10 Jiwa/Ha	>10 Jiwa/Ha	Class / Maximum Class Value
		Ratio of Vulnerable Groups			
Sex Ratio (10%)	40	>100	= 100	< 100	

Source: Bencana, 2014

Table 3 serves as the reference for determining the social vulnerability index. To obtain this value, population density was calculated by dividing the total population by the area of each village, which was then classified into three categories with a weight of 60%. The sex ratio was determined by dividing the number of male residents by the number of female residents and multiplying the result by 100, with a weight of 40 %. The classification of the sex ratio was adjusted to reflect the higher vulnerability of female populations in each village. This study is limited by the availability of social data obtained from (Badan Pusat Stastistik Kabupaten Tapanuli Tengah, 2023), so the social vulnerability analysis uses only two main parameters: population density and sex ratio. Nevertheless, this approach remains relevant and is supported by previous research (Prihartanto et al., 2023) used population density, vulnerable groups, and the number of tourists as parameters to analyze social vulnerability to tsunamis in the Bayah Dome Geopark. Additionally, (Widyanti et al., 2023) also used two main parameters population density and sex ratio to determine the social vulnerability index in Mempawah Hilir Subdistrict. Thus, the parameters used in this study are deemed capable of representing the baseline conditions of the community's social vulnerability to potential tsunami disasters in Barus Subdistrict, Tapanuli Tengah Regency.

2. 5 Tsunami Hazard and Risk Modeling

Tsunami inundation modeling was carried out using an equation formula (Berryman, 2006), which is based on guidelines from the National Disaster Management Agency (Nugroho et al., 2018) and has been the model formulation applied in a previous study (Septiangga, 2019). This study is an extension of a previous study that used numerical modeling based on the 2005 Nias–Simeulue earthquake scenario with a magnitude of 8.6 Mw and indicated that the Barus region is at risk of experiencing a tsunami with inundation heights ranging from 3 to 8 meters (Sinambela and Sukanta, 2022). Therefore, this study uses a tsunami wave height scenario along of 16 meters from the shoreline to represent a more conservative condition based on historical tsunami records and the high level of seismic activity in the Sumatra megathrust zone (PVMBG, 2023) , which can provide accurate information on the distribution of the tsunami inundation index. The modeling incorporates five key parameters: slope gradient, land cover roughness coefficient, tsunami height, coastline data, and social vulnerability.

$$Hloss = \left(\frac{167n^2}{H_0^{1/3}}\right) + 5\sin S \qquad (1)$$

The parameters used in tsunami inundation modeling include the decrease in water height upon reaching land (H), the surface roughness coefficient (n) obtained from digitized land cover data, the tsunami height at the coastline (H_0) of 16 m, and the slope gradient (S) derived from DEM data processing. The accuracy of topographic data, such as the National Geospatial Information Agency's DEMNAS and DEM, significantly influences the precision of tsunami inundation simulations and evacuation route planning (Sihombing et al., 2024). These parameters are integrated into a GIS system and processed using the Model Builder in ArcGIS to generate tsunami hazard maps. The digitized and validated coastline, using imagery from SAS Planet and coastline data from the Indonesian Topographic Map (RBI), is used to model the spatial distribution of tsunami wave energy from the ocean to the land. The results of this modeling can then be integrated with GIS-based network analysis to determine optimal evacuation routes to safe locations (Wijayanto et al., 2025), taking into account key parameters such as wave arrival time and run-up height in assessing tsunami hazard levels in coastal areas (Chaerul et al., 2026). However, this model has limitations because it does not take into account in detail wave dynamics, bathymetric interactions, and changes in coastal morphology; therefore, the results are used as an initial approach to supporting tsunami disaster mitigation planning and evacuation route analysis in Barus Subdistrict, Central Tapanuli Regency.

Tsunami risk modeling was carried out using the Crunch model to generate a tsunami risk map. The Crunch model calculation was performed by multiplying the hazard component (H) from the hazard modeling with the social vulnerability component (V), which was determined based on population density and the sex ratio.

2. 6 Determination of Evacuation Points

The locations of evacuation points were determined using a scoring and weighting method based on four main criteria, as outlined in Table 4.

Table 4. Scoring Values and Criteria for Determining Tsunami Evacuation Points

Parameter	Criteria	Scoring Value
Building Function (Land Use)	Residential Area	1
	Health Facility	2
	Government or Private Office	3
	School or Mosque	4
Elevation (meters above sea level)	0 - 10	1
	25 - 10	2
	> 25	3
Distance from Shoreline (meters)	0 - 500	1
	501 - 1000	2
	1001 - 1500	3
	1501 - 3000	4
	>3000	5
Hazard Level	Low	3
	Medium	2
	High	1

Source: Suharyanto, 2012

Table 4 serves as the basis for determining evacuation points that meet the building function criteria, which are classified into four categories based on 127 building function data entries from the RBI of Barus District. The elevation criterion was obtained from DEM data processing and classified into three categories using the Reclassify tool. The distance-from-coastline criterion was derived from digitized coastline data using the Buffer feature. The hazard-level criterion was calculated using Equation (1). Each criterion was spatially processed through the overlay method in ArcGIS and classified into three categories: not suitable, quite suitable, and very suitable. These results were then validated through remote sensing using Google Earth Pro to ensure the physical feasibility of the evacuation sites. The validation process referred to the Guidelines for Evacuation Site Planning issued by the Indonesian National Disaster Management Agency (Badan Nasional Penanggulangan Bencana, 2018)

2. 7 Evacuation Route Modeling

Tsunami evacuation route modeling was conducted using the Network Analysis method with the Closest Facility feature in ArcGIS. This analysis aims to determine the fastest route from the Temporary Evacuation Point (TEP) to the Final Evacuation Point (FEP) based on road network data sourced from the Indonesian Topographic Map (RBI). The parameters considered include road length and type, connectivity, accessibility, road conditions, and the elevation of evacuation locations obtained from the integration of tsunami hazard and risk maps. Road conditions were evaluated through the interpretation of high-resolution imagery using Google Earth Pro. Travel time estimates are calculated using an average human walking speed of 1.2 m/s to assess the effectiveness and efficiency of each route. Thus, the determination of evacuation routes is not only based on the shortest route but also considers the spatial conditions of the road network and the suitability of the evacuation location.

3. Result and Discussion

3.1 Hazard Map

The tsunami hazard map was generated through calculations based on Equation (1), integrated with spatial analysis using the Model Builder tool. Five main parameters were applied: slope gradient, roughness coefficient values, tsunami height scenario, coastline data, and data processing through fuzzy membership in ArcGIS Map 10.8. Tsunami hazard modeling identified three hazard levels: low, medium, and high, based on a tsunami wave height scenario of 16 meters. This classification represents estimates of tsunami inundation heights on land, with the high-hazard zone ranging from 0–6.5 m, the medium hazard zone from 6.5–11.6 m, and the low hazard zone from 11.6–15.9 m. The high-hazard zone is generally distributed across villages located along the southern coast of Barus Subdistrict, which feature low-lying topography and proximity to the shoreline, making them susceptible to greater tsunami inundation. These results are consistent with the research by (Waluyo and Wardhani, 2021), which indicates that coastal areas with gentle topography and low elevation have a higher vulnerability to tsunami disasters.

Spatially, two villages fall within the high-risk tsunami zone: Pasar Terandam Village, covering 0.413 km^2 (18.16 %) of its total area, and Pasar Batu Gerigis Village, covering 0.229 km^2 (10.11 %) of its total area. This indicates that both villages face a high level of exposure to potential inundation if a tsunami reaches its maximum height. These findings are further supported by (Handoyo et al., 2023), which emphasizes that areas with low roughness coefficients are more vulnerable to the destructive force of tsunamis. Meanwhile, the other five villages Kampung Solok, Kedai Gedang, Kinali, Padang Masiang, and Sigambo-gambo fall within the low-risk zone. This classification is mainly due to the larger portions of their areas lying within the low- and medium-risk zones, with only relatively small sections exposed to high-risk hazards. For example, Kedai Gedang Village has a safe zone of 0.568 km^2 out of a total area of 0.855 km^2. Similarly,

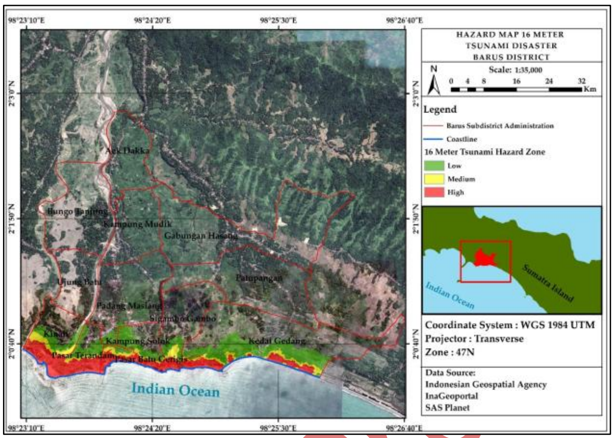

Fig. 2 The tsunami hazard map of Barus District under the 16-meter tsunami scenario illustrates three hazard levels: low (green), medium (yellow), and high (red), along with administrative boundaries and the coastline (Source: Data Processing, 2025)

Kinali Village shows a fairly balanced distribution of zones, but without significant dominance in the high-risk category, it remains classified as low-risk. Overall, the flat topography and low roughness coefficient values play an important role in determining the classification and spread of tsunami inundation under the 16-meter scenario in Barus District. These findings are consistent with (Latue and Latue, 2023), which reported that flat topography and low roughness coefficients increase the likelihood of areas being placed in the high-risk tsunami zone.

The implications of these findings highlight the importance of strengthening spatial-based disaster mitigation policies. Villages categorized as high-risk zones require more intensive management, while those in low-risk zones should still receive attention through disaster education initiatives.

Table 5. The tsunami hazard analysis for the 16-meter scenario in Barus District shows the affected land area and the percentage of inundation classified into low, medium, and high hazard zones.

Village Name	Low (km^2)	Medium (km^2)	High (km^2)	Total Area (km^2)	Percentage (%)	Classification
Pasar Batu Gerigis	0.039	0.038	0.151	0.229	10.11	High
Pasar Terandam	0.133	0.036	0.242	0.413	18.16	High
Kampung Solok	0.171	0.016	0.013	0.201	8.84	Low
Kedai Gedang	0.568	0.094	0.192	0.855	37.59	Low
Kinali	0.130	0.078	0.130	0.339	14.91	Low
Padang Masiang	0.065	0	0	0.065	2.88	Low
Sigambo-gambo	0.078	0.045	0.045	0.170	7.47	Low
Total				2,274	100	

Source: Data Processing, 2025

3.2 Risk Map

The tsunami risk map of Barus District was developed using an overlay method that combines the hazard analysis map with the social vulnerability map. The hazard analysis was derived from Equation (1), calculated through spatial integration using five key parameters in the model builder. Meanwhile, the vulnerability analysis was determined through a scoring and weighting system based on population density data and the sex ratio, under the assumption that women are more vulnerable to tsunami disasters. This assumption is supported by (Ramailis and Sakir, 2024), which found that women in coastal areas have a different adaptive capacity compared to men. The final results of this analysis are presented in the map shown in Figure 3. Figure 3 illustrates the distribution of tsunami risk areas in Barus District under the 16-meter scenario, divided into three zones. The red zone represents areas with high risk, the yellow zone indicates medium risk, and the green zone shows low-risk areas.

The map reveals that red zones are associated with high-risk index values, largely influenced by high population density, even though the sex ratio is not a dominant factor. These zones are concentrated along the coastline, particularly in Pasar Batu Gerigis Village, which has a population density of 63.16 people per hectare and a sex ratio of 104.6, meaning the male population slightly outnumbers the female population. Similarly, Pasar Terandam Village records a population density of 53.14 people per hectare and a sex ratio of 106.52.

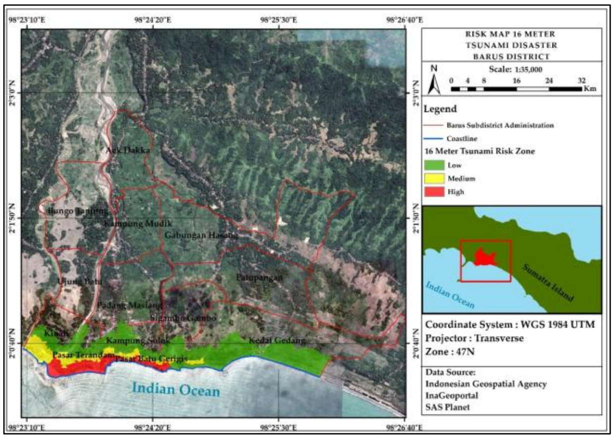

Fig. 3 The tsunami risk map of Barus District under the 16-meter tsunami scenario indicates three risk levels: low (green), medium (yellow), and high (red). The map also shows administrative boundaries and the coastline (Source: Data Processing, 2025)

Both villages have total affected areas of 0.2 km² and 0.413 km², respectively, with high-risk zone proportions of 0.113 km² (49.34 %) and 0.187 km² (45.27 %), as shown in Table 6. These results align with (Susetyo et al., 2025), which found that densely populated coastal areas tend to have higher vulnerability levels, even when the sex ratio is not a major factor. The yellow and green zones in Figure 3 represent areas with low to moderate vulnerability index values. This indicates that these regions are characterized by a male-dominated sex ratio and relatively low population density. These zones are spread across five villages: Kampung Solok, Kedai Gedang, Kinali, Padang Masiang, and Sigambo-gambo.In Figure 3, Kinali Village appears almost evenly divided between yellow (medium) and green (low) zones. This suggests that the village has a higher proportion of female residents despite its low population density. Table 6 supports this finding, showing that Kinali Village has nearly equal areas of safe and moderate zones 0.184 km² (low) and 0.153 km² (medium).

From the results, the total area at risk was found to be 2.274 km². Within this, two villages Pasar Batu Gerigis and Pasar Terandam were identified as having both a high hazard level and a high vulnerability index, covering a total of 0.64 km². These areas are therefore classified as high-risk tsunami zones. This finding is consistent with (Deliany Putri and Muhammad, 2019) , which showed that regions with a high vulnerability index generally correspond to high risk levels, largely influenced by population density. It is further supported by (Suparno, Retno Utami Agung Wiyono, Entin Hidayah, 2023) , which concluded that villages located in high-hazard zones with high vulnerability are classified as high-risk areas. Likewise, (Sambah et al., 2019) emphasized that risk levels are shaped by factors such as elevation, distance from the coastline, and social vulnerability at the village level. Based on these findings, greater focus is needed on raising community awareness and strengthening disaster mitigation efforts in areas classified as high-risk zone.

Table 6. The tsunami risk analysis for the 16-meter scenario in Barus Subdistrict shows the total affected area and the percentage of inundation across low, medium, and high hazard classifications.

Village Name	Low (km²)	Medium (km²)	High (km²)	Total Area (km²)	Percentage (%)	Classification
Pasar Batu Gerigis	0.047	0.068	0.113	0.229	10.08	High
Pasar Terandam	0.142	0.083	0.187	0.413	18.16	High
Kampung Solok	0.175	0.019	0.007	0.201	8.87	Low
Kedai Gedang	0.855	0.000	0.00033	0.855	37.61	Low
Kinali	0.184	0.153	0.0016	0.339	14.91	Low
Padang Masiang	0.065	0.000	0.000	0.065	2.88	Low
Sigambo Gambo	0.137	0.032	0.00033	0.169	7.45	Low
Total				2,274	100	

Source: Data Processing, 2025

3.3 Evacuation Points Analysis Map

The evacuation point analysis was carried out using a spatial approach by assigning scores to each indicator listed in Table 4. These indicators were scored and then intersected using ArcGIS software. The cumulative scores were then classified into three categories: not suitable, quite suitable, and very suitable. The spatial analysis results of the evacuation points are presented in Figure 4.

Figure 4 presents the evacuation points classified into three categories. Based on the map, 34 out of 127 points were identified as not suitable, 70 points as quite suitable, and 23 points as very suitable. The figure also indicates that the higher the total score of each indicator, the more appropriate the location is for evacuation purposes. These results are consistent with (Indah Cahyaning Sari, I Nyoman Suluh Wijaya, 2020) , which found that evacuation points with higher total scores were more suitable.

From this analysis, further validation was carried out through road-tracing using remote sensing with the help of Google Earth Pro, without conducting direct field surveys. This method aligns with the approach of (Mutaqin et al., 2023) , which reviewed shelters using remote sensing and Google Maps to determine suitable shelter locations.

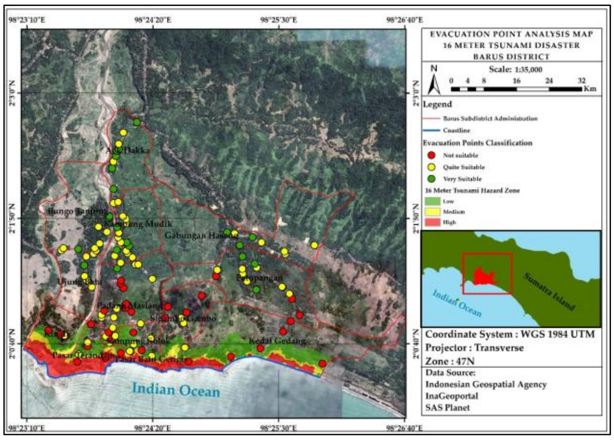

Fig. 4 The evacuation point analysis map of Barus Subdistrict under the 16-meter tsunami inundation scenario shows the classification of evacuation points into three categories: very suitable (green), quite suitable (yellow), and not suitable (red) (Source: Data Processing, 2025).

Based on the review results, five Temporary Evacuation Point (TEP) and two Final Evacuation Point (FEP) were identified. The number of Final Evacuation Point (FEP) is consistent with previous research (Sinambela and Sukanta, 2022). However, there is a difference in the number of Final

Evacuation Point (FEP), as one TEP did not meet the criteria for an evacuation site due to its indicator score. This particular TEP is located within a danger zone. The results are presented in Table 7 and Figure 5.

Table 7. The locations of final evacuation point (FEP) and temporary evacuation points (TEP) were determined through evacuation point analysis based on key indicators, including elevation, distance from the shoreline, hazard level, and road accessibility to each site.

No	Place	Long	Lat	Image	Description
				Final Evacuation Point (FEP)	
1	HKBP Church	98,4032	2,04539		1. Located at an elevation of more than 25 meters above sea level. 2. Situated more than 3,000 meters from the shoreline. 3. Classified as safe, with a hazard level greater than 15.9 meters. 4. Positioned along a local road with smooth and wide access.
2	Catholic Church	98,417	2,02791		1. Located at an elevation of 10–25 meters above sea level. 2. Situated 1,501–3,000 meters from the shoreline. 3. Classified as safe, with a hazard level greater than 15.9 meters. 4. Positioned along a collector road with smooth and wide access.
				Temporary Evacuation Point (TEP)	
1	Barus Sports Hall	98,4037	2,01424		1. Classified as safe, with a hazard level greater than 15.9 meters. 2. Located along a local road with smooth and wide access. 3. Positioned 501–1,000 meters from the shoreline. 4. Situated at an elevation of 0–10 meters above sea level.
2	Ilir Barus Mosque	98,4103	2,01428		1. Classified as safe, with a hazard level greater than 15.9 meters. 2. Located on a neighborhood road with smooth and wide access. 3. Positioned 501–1,000 meters from the shoreline. 4. Situated at an elevation of 0–10 meters above sea level.
3	Barus State Junior High School 1 (SMPN 1 Barus)	98,3988	2,0128		1. Classified as safe, with a hazard level greater than 15.9 meters. 2. Located along a local road with smooth and wide access. 3. Positioned 501–1,000 meters from the shoreline. 4. Situated at an elevation of 0–10 meters above sea level.
4	Barus State Islamic Senior High School (MAN Barus)	98,3977	2.01557		1. Classified as safe, with a hazard level greater than 15.9 meters. 2. Located along a local road with smooth and wide access. 3. Positioned 501–1,000 meters from the shoreline. 4. Situated at an elevation of 0–10 meters above sea level.
5	Al Mutaqqin Mosque	98,392	2.01236		1. Classified as safe, with a hazard level greater than 15.9 meters. 2. Located along a local road with wide concrete access. 3. Positioned 501–1,000 meters from the shoreline. 4. Situated at an elevation of 0–10 meters above sea level.

Source: Data Processing, 2025

Table 7 presents the detailed results of the final and temporary evacuation points analyzed using the scoring method. As illustrated in Figure 5, the distribution of tsunami evacuation points was assessed based on factors such as topography, road conditions, distance from the shoreline, and hazard zones. The figure identifies two final evacuation sites located at elevations above 25 meters above sea level, more than 300 meters from the coastline, within low-hazard zones, and accessible by good road conditions. These points are situated at the HKBP Church and the Catholic Church. In addition, five temporary evacuation points were identified, each located at elevations between 0–10 meters above sea level, 500–1000 meters from the shoreline, also within low-hazard zones, and connected by good roads. These points include the sports hall, Ilir Barus Mosque, SMPN 1 Barus, MAN Barus, and Al Mutaqqin Mosque. These findings serve as an important reference for disaster mitigation efforts, emphasizing the need to establish evacuation sites that are evenly distributed in accordance with population density and road accessibility.

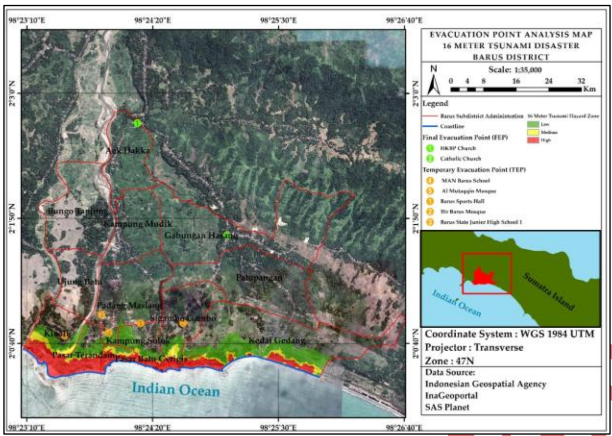

Fig 5. The tsunami evacuation point map for Barus District under the 16-meter inundation scenario shows the spatial distribution of final evacuation point (FEP) and temporary evacuation points (TEP) (Source: Data Processing, 2025).

3.4 Evacuation Route Map

The evacuation route map was modeled using the network analysis method with the closest facility feature to determine the fastest evacuation routes based on travel time, while also taking into account the types of roads from the road network data. The results are presented in Figure 6 (A-B).

Figures 6 (A-B) illustrate the evacuation routes, directions, and estimated travel times from TEP to FEP, with classifications represented by different colors. Each color on the map indicates that all TES are accessible to every TEP. The distribution pattern of the evacuation routes suggests that the network is functionally well-connected. For example, several FEP are located along arterial roads that link to other districts and provinces, ensuring that aid can be delivered efficiently. Similarly, TEP located along local roads are still connected to FEP on arterial routes, allowing assistance to reach these points as well. From these maps, the analysis also provides corresponding travel times and distances, as summarized in Table 8.

Based on the results presented in Table 8, the fastest evacuation route was recorded from TEP 2 (Ilir Barus Mosque) to FEP 2 (Catholic Church), with a travel time of 25.06 minutes. In contrast, the longest route was from TEP 5 (Al Mutaqqin Mosque) to FEP 1 (HKBP Church), requiring 65.74 minutes. These differences are influenced by the scenario used, including travel distance, road conditions, and the type of roads along the route. These findings are consistent with (Liu et al., 2025) , which also reported that evacuation times vary depending on distance, elevation, and road network characteristics. The evacuation time simulation in this study was conducted under ideal conditions, namely a constant walking speed of 1.2 m/s and a road network in normal condition without obstacles or traffic congestion.

Table 8. The analysis of tsunami evacuation routes in Barus District

No	FEP (Start)	Destination Point	TEP (Finish)	Time (Minutes)	Distance (m)
1	2	Barus Sports Hall – Catholic Church	1	33.04	2,379.19
2	2	Ilir Barus Mosque – Catholic Church	2	25.06	1,804.79
3	2	SMPN 1 Barus – Catholic Church	3	41.57	2,993.27
4	2	MAN Barus – Catholic Church	4	44.97	3,237.97
5	2	Al Mutaqqin Mosque – Catholic Church	5	56.26	4,051.27
6	1	Barus Sports Hall – HKBP Church	1	55.62	4,005.12
7	1	Ilir Barus Mosque – HKBP Church	2	62.02	4,465.74
8	1	SMPN 1 Barus – HKBP Church	3	56.11	4,040.01
9	1	MAN Barus – HKBP Church	4	54.36	3,914.27
10	1	Al Mutaqqin Mosque – HKBP Church	5	65.74	4,733.80

Source: Data Processing, 2025

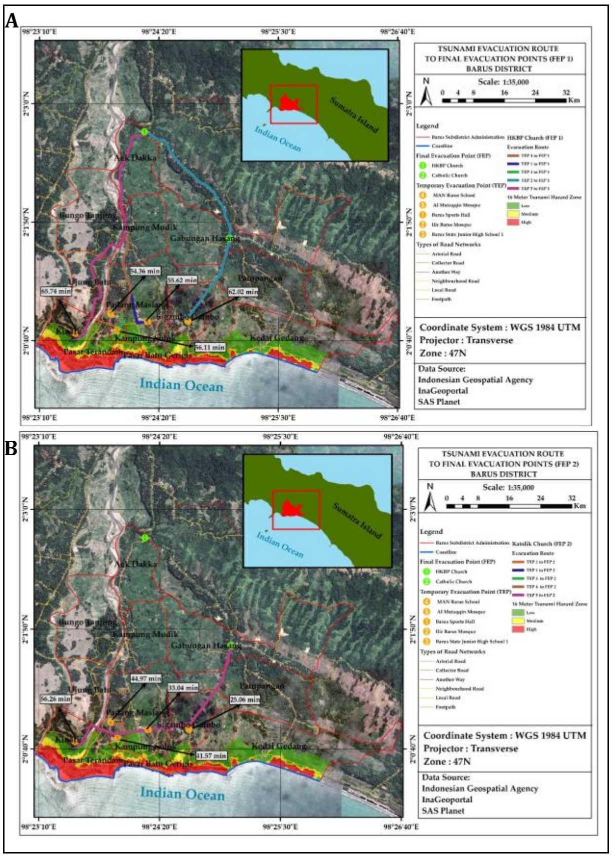

Fig. 6 The tsunami evacuation route map for Barus District under the 16-meter inundation scenario shows the optimal routes

leading to FEP 1 (the HKBP Church) (A), FEP 2 (the Catholic Church) (B)

The resulting evacuation routes were then validated through the interpretation of high-resolution imagery using Google Earth Pro to assess elevation, physical conditions, and road types without the need for direct field surveys. This approach aligns with (Mutaqin et al., 2023), who utilized remote sensing aided by Google Maps to determine effective shelter locations and evacuation times in Carita Village, while also adhering to the tsunami evacuation site planning guidelines from (Badan Nasional Penanggulangan Bencana, 2018), Thus, the resulting evacuation routes are not only based on the shortest paths but also consider the spatial conditions of the road network, topographic characteristics, and the suitability of evacuation sites. This analysis underscores the importance of disaster mitigation and community preparedness, given that during the 2004 Indian Ocean earthquake and tsunami, tsunami waves reached Banda Aceh approximately 45 minutes after a 9.0 Mw earthquake occurred off the coast of Sumatra. Therefore, evacuation routes with travel times exceeding 45 minutes are categorized as critical and require re-evaluation to ensure the safety of the population (Rao, 2006).

4. Conclusion

The tsunami hazard analysis for the 16-meter scenario in Barus District covered a total area of 2.27 km², divided into three categories. High-hazard zones were identified in Pasar Batu Gerigis and Pasar Terandam villages, with a combined area of 0.64 km². The distribution of these hazard zones is influenced by flat slope conditions, low surface roughness values, and close proximity to the coastline.

The tsunami risk analysis, also classified into three categories, revealed two villages Pasar Terandam and Pasar Batu Gerigis falling into the high-risk zone, with the same total area of 0.64 km². The overlap between high-hazard and high-risk zones indicates regions with significant physical threat potential, compounded by high levels of social vulnerability. Spatially, this combination produces areas of elevated risk, which must be prioritized in disaster mitigation efforts.

The evacuation route modeling results show that travel times from TEP to FEP range between 25 and 66 minutes, assuming an average walking speed of 1.2 m/s. The route leading to TEP 2 (the Catholic Church) requires less time compared to FEP 1 (the HKBP Church), which takes over 60 minutes. This makes FEP 1 a critical route that requires special attention in tsunami emergency response planning.

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