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PLANNING OF TSUNAMI EVACUATION SITES AND ROUTES BASED ON A MEGATHRUST SCENARIO TO SUPPORT THE TSUNAMI READY PROGRAM: A CASE STUDY OF PENGAMBENGAN VILLAGE, INDONESIA

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ABSTRACT

Pengambengan Village, located in Jembrana Regency, is highly susceptible to tsunami disasters, necessitating the implementation of mitigation measures through the Tsunami Ready Program. This study aims to develop a tsunami hazard map and identify tsunami evacuation sites and route scenarios in Pengambengan Village to meet the Tsunami Ready indicators. The tsunami hazard map was generated by tsunami modeling based on a worst-case scenario on the Sumba Megathrust segment with Mw 8.5 using the COMCOT and QGIS software. Recommended evacuation sites and routes were determined through network analysis using GIS-based network analysis. The tsunami modeling results indicate that approximately 91.7 percent of the area in Pengambengan Village is affected by tsunamis, with maximum flow depths ranging from 6 to 10 meters in Banjar Ketapang Muara and Banjar Kombanding. The estimated tsunami arrival time near Pengambengan Beach is approximately 37 minutes, with maximum tsunami inundation extending up to 1.6 kilometers. The service area analysis identified four potential tsunami evacuation sites in Pengambengan Village. However, Banjar Ketapang Muara remains inadequately covered due to a lack of suitable evacuation sites and buildings. This study determined seven optimal evacuation routes to the proposed tsunami evacuation sites. Additionally, the findings suggest constructing a vertical evacuation site in Banjar Ketapang Muara to address the identified gap. The outcomes of this study contribute to supporting the Tsunami Ready Program in Pengambengan Village.

***Keywords**: GIS; network analysis; tsunami hazard; tsunami ready.*

A. INTRODUCTION

Pengambengan Village is one of the coastal areas in Bali that is prone to earthquake and tsunami hazards. In addition to being at risk of earthquakes originating from the Megathrust zone and the Flores Back Arc Thrust, there is also the Tegal Badeng fault on land (Pratama et al., 2023). According to data from the BMKG Catalogue of Destructive Earthquakes (BMKG, 2024), the Jembrana region has been hit several times by earthquakes with damaging impacts, such as the Situbondo Earthquake on 10 October 2018, the South Bali Earthquake on 22 March 2017, and the Bali Earthquake on 14 July 1976. Furthermore, according to Tsuji et al. (1995), the 1994 Banyuwangi Tsunami also affected the Jembrana area.

Large earthquakes and tsunamis occur infrequently (Parwanto & Oyama, 2014). However, these natural hazards possess a high potential for causing significant loss of life and extensive damage. Between 1800 and 1999, Indonesia recorded approximately 54,100 fatalities from tsunami events and around 10,600 deaths resulting from destructive

earthquakes (Latief et al., 2000). Consequently, disaster mitigation efforts are essential to anticipate and reduce the risks associated with earthquakes and tsunamis. One such initiative is the Tsunami Ready Program established by the UNESCO Intergovernmental Oceanographic Commission (IOC), which aims to build resilient communities through enhanced awareness and preparedness strategies to safeguard lives, livelihoods, and property from tsunami threats in various regions, including Indonesia. To be recognized as a Tsunami Ready Community, a village or local community must fulfill twelve indicators. These indicators emphasize that tsunami preparedness is not limited to hazard assessment but requires an integrated approach combining scientific analysis, infrastructure planning, and community engagement. Given its location on the western coast of Bali and its exposure to tsunami hazards, Pengambengan Village requires comprehensive disaster mitigation and preparedness measures. A crucial component of such efforts is achieving Tsunami Ready Community recognition. Among the twelve indicators, Indicators 1 and 4 are particularly relevant to this study, namely creating a tsunami hazard map and designating evacuation routes.

Research on tsunami hazards in Bali has been carried out for various objectives, including the assessment of tsunami hazard levels (Khomarudin et al., 2010; Sinaga et al., 2011), mitigation strategies (Hall et al., 2019), and risk reduction measures (Sakya et al., 2023; Surtiari et al., 2024; Wegscheider et al., 2011). The studies have predominantly concentrated on tourism areas along the southern and eastern coasts of the island. In contrast, relatively limited research has addressed tsunami hazards and evacuation planning along the western coast of Bali. This research gap is particularly important for coastal communities such as Pengambengan Village, where detailed tsunami hazard assessment and evacuation planning are needed to support local disaster preparedness.

Accordingly, this study aims to contribute to the fulfillment of Tsunami Ready Indicator 1, which concerns the preparation of tsunami hazard maps, and Indicator 4, which involves the identification of temporary evacuation sites and routes through network analysis in Pengambengan Village. Unlike previous studies that have primarily focused on southern and eastern Bali, this research provides a detailed tsunami hazard and evacuation assessment for the western coast of Bali at the *banjar* scale using a worst-case seismic gap scenario. By integrating tsunami hazard modeling with evacuation site and route analysis, this study supports the implementation of Tsunami Ready indicators while addressing the knowledge gap in tsunami preparedness along the western coast of Bali.

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B. MATERIALS AND METHODS

a. Study Area

Pengambengan Village is a coastal area located in Negara District, Jembrana Regency, Bali Province, Indonesia. Pengambengan Village has an approximate area of 607 hectares and is located in the south of Jembrana Regency, precisely at coordinates between 8° 23' 1.3704" S - 8° 23' 40.668" S to 114° 34' 31.962" E - 114° 37' 24.168" E as illustrated in Figure 1. According to Pengambengan Village government data, the total population of Pengambengan Village is 13,387 people, consisting of 6,814 men and 6,573 women. In Bali, a *banjar* (a traditional community or neighborhood organization similar to a neighborhood association) plays an important role in local governance. There are five *banjars* in Pengambengan Village, namely Banjar Kombanding, Banjar Ketapang Muara, Banjar Ketapang, Banjar Munduk, and Banjar Kelapa Balian. As an area on the coast, Pengambengan Village is prone to tsunamis.

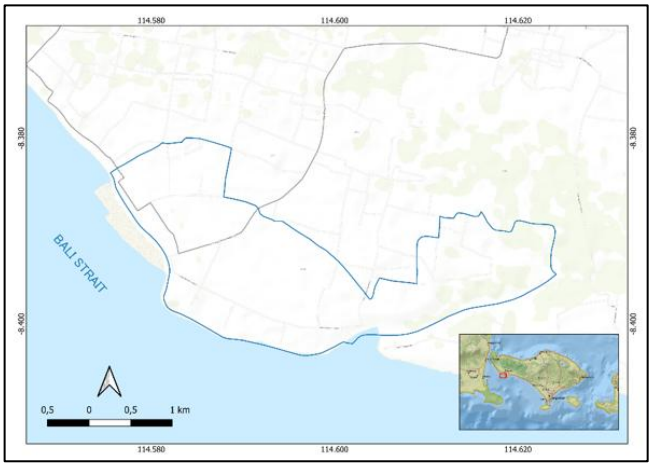


Figure 1. Study area in Pengambengan Village

Source: Data Processing, 2026

b. Data Collection

This study utilized various input data, including bathymetry and topography, to perform tsunami modeling. The topographic data used in this research are derived from the Rupa Bumi Indonesia (RBI) dataset, with a resolution of 12.5 meters. Then, bathymetry data are sourced from the BATNAS dataset, with a resolution of 180 meters, both provided by the Geospatial Information Agency. Additionally, earthquake source parameters essential for the modeling process are described in the following section. Land cover data, required to determine the friction coefficient for tsunami modeling, were obtained from the Ministry of Environment and Forestry. The land cover in Pengambengan Village includes settlements, rice fields, ponds, harbors, and rivers. For conducting network analysis, road network data

from the Geospatial Information Agency were employed. Furthermore, this study incorporates administrative boundary data; provincial and district-level boundaries were sourced from the Geospatial Information Agency, while administrative data at the *banjar* level were acquired from the Central Bureau of Statistics. Google Maps satellite imagery (accessed on February 2, 2025) was also used to identify the tsunami evacuation site recommendation.

c. Data Processing

Tsunami Source Identification

This study adopted a worst-case tsunami scenario based on the maximum credible earthquake magnitude proposed by the Indonesian National Earthquake Study Center (PuSGeN, 2024). The Sumba Megathrust segment is estimated to be capable of generating earthquakes with a maximum moment magnitude of Mw 8.5, based on its tectonic setting, segment length, and historical seismicity.

The tsunami source location in this study was determined by analyzing the distribution of tsunami seismic gaps in the subduction zone between Bali and West Nusa Tenggara (NTB), based on historical tsunami events. This gap area is recognized as a seismic gap, defined as a spatial gap in the distribution of rupture zones associated with major earthquakes along a seismic belt (Mogi, 1979).

In addition to the earthquake's location, other earthquake source parameters are needed for modeling, obtained using scientific references and mathematical calculations. The earthquake source parameters used in this study were as follows:

- The rigidity used in the model is 30 GPa for a source depth of about 30 km (Bilek & Lay, 1999; Tanioka et al., 2017);
- The depth, strike, and dip parameters were obtained from the USGS Sumba segment subduction model (Hayes et al., 2018);
- The bottom friction coefficient used in this study was obtained from the land cover classification in the COMCOT manual (Wang & Power, 2011);

The length and width parameters of the fault plane were estimated using the empirical relationships of Wells and Coppersmith (1994), which relate earthquake magnitude to fault length and width. Meanwhile, to obtain the vertical dislocation value, the magnitude and seismic moment relationship equation from Hanks & Kanamori (1979) was used. We use a multi-fault model represented by the model shown in Figure 2, and the parameters obtained are listed in Table 1. Moreover, the three subfaults collectively represent the Mw 8.5

earthquake scenario, while the moment magnitude values listed in Table 1 represent the equivalent magnitude assigned to each individual subfault.

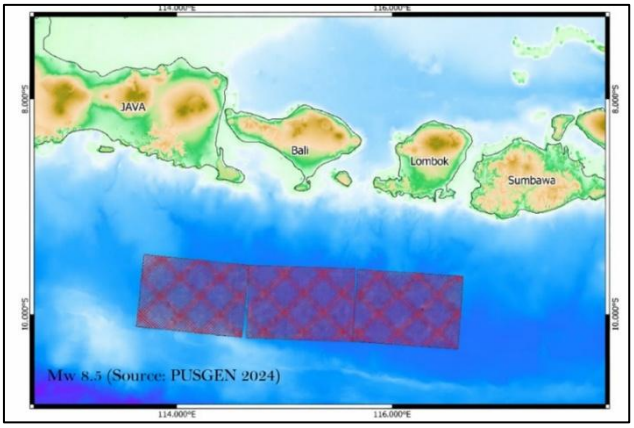


Figure 2. Fault model used in the tsunami simulation.

Source: Data Processing, 2026

Table 1. Earthquake Source Parameters

Subfault	Sumba Megathrust										
	Epicenter (°)		Mag	Depth	Focal Mechanism			Dimension		Dislocation	Rigidity
	Lon	Lat	Mw	km	Strike	Dip	Rake	L (km)	W (km)	(m)	(GPa)
Fault 1	114.1438	-9.822	8.15	31	277	19.7	90	108	75	8.697	30
Fault 2	115.1421	-9.888	8.22	30	273	18.4	90	108	75	11.076	30
Fault 3	116.1404	-9.941	8.18	29.5	274	17.5	90	108	75	9.647	30

Tsunami Modeling

The numerical tsunami modeling in this study was performed using COMCOT (Cornell Multi-grid Coupled Tsunami Model) software (Wang & Power, 2011), which can be used to reconstruct tsunami wave propagation from its source. COMCOT is a tsunami modeling software based on the numerical solution of the shallow water wave equations. COMCOT has been widely utilized to simulate numerous historical tsunami events, such as the 2004 Indian Ocean tsunami (Syamsidik et al., 2017) and the 2018 Palu tsunami (Gusman et al., 2019). COMCOT uses a staggered leap-frog scheme with the finite difference method to solve linear and non-linear long wave equations.

The results of the tsunami modeling are the flow depth and the tsunami arrival time. Then, these results were subsequently used to develop the tsunami hazard map. To obtain more detailed results while maintaining computational efficiency, a five-layer nested grid system was used, with a spatial resolution of 10 m in the innermost layer.

Network Analysis – Service Area

The service area analysis was conducted to determine the spatial coverage of the recommended evacuation sites within the available physical evacuation time. The available evacuation time was calculated from the estimated tsunami arrival time of approximately 37 minutes, after accounting for 6 minutes for technical warning dissemination and 7 minutes for community response as suggested by Yunarto & Sari (2018). Thus, the available physical evacuation time was 24 minutes ($37 - 6 - 7 = 24$ minutes). This 24-minute threshold was subsequently used to evaluate whether the recommended evacuation sites could be reached within the available evacuation time. This calculation was based on the empirical formula from Post et al. (2009).

The resulting service area polygons represent zones of equal travel time from each evacuation site, which can be further analyzed to assess coverage gaps and optimize the placement of additional shelters or evacuation routes. This method has been widely applied in tsunami evacuation studies, particularly for assessing evacuation potential in coastal areas (Ashar et al., 2018).

Network Analysis – Shortest Route

The shortest route analysis identifies evacuation routes with the minimum distance to designated evacuation sites. This analysis utilizes input data, beginning with a starting point. In this study, the starting points are referred to as recommended gathering points, which are determined based on the criteria of road intersections within a travel time of ≤ 5 minutes from the center of the village settlement, as outlined by Indira & Manessa (2023). The assumed walking speed used in the analysis is 0.751 m/s, representing the average walking speed of elderly individuals, to ensure that all residents can evacuate within the required time frame (Indira & Manessa, 2023). The endpoints of the analysis are the designated tsunami evacuation sites identified in this study. The analysis was conducted using QGIS software, which calculates the shortest path between two points along the road network and visualizes these paths on the map.

C. RESULTS AND DISCUSSION

Tsunami Source Design

The initial tsunami conditions were represented by seabed uplift and subsidence caused by sudden movement of the Earth's crust, which displaced the overlying water column. The snapshot from Layer 1 was selected because it encompasses the earthquake epicenter and the study area.

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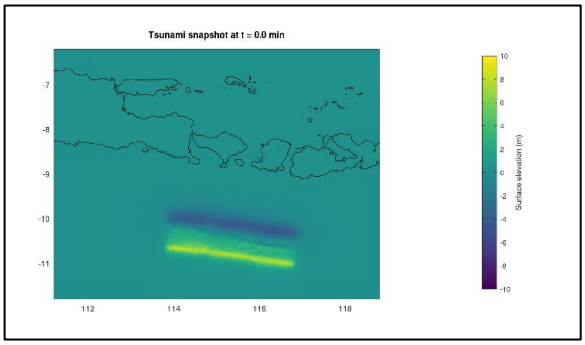


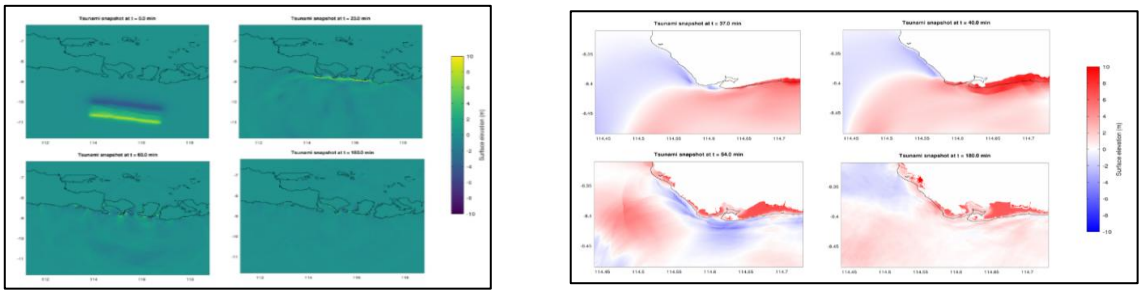
Figure 3. Initial tsunami conditions from the worst-case scenario, the blue color for subsidence and yellow color for uplift. Source: Data Processing, 2026

Figure 3 shows the initial conditions of the tsunami, depicting sea level changes around the epicenter. The earthquake scenario used in COMCOT was represented through a source model that defines the earthquake fault area originating from the epicenter. This fault area is determined based on calculations derived from scaling law relationships. Changes in sea level around the epicenter are between -4.6 m to 8.1 m.

Tsunami Wave Propagation

Tsunami modeling in this study was carried out over a 3-hour simulation period, with wave propagation computed at 60-second intervals. The simulation produced a series of snapshots illustrating tsunami wave propagation at different time steps following the earthquake. These snapshots were generated using layer 1 (the largest layer) to provide a clearer visualization of tsunami wave propagation from the earthquake epicenter toward the coast.

The propagation of tsunami waves in layer 1 is shown in Figure 4, where the color scale from blue to yellow on the right side of the image indicates wave height. The modeling results suggest that tsunami waves propagate from the earthquake source in all directions. As the tsunami waves approach the coast, their wavelength decreases while their amplitude increases, because tsunami wave speed depends on water depth.



(a) (b)

Figure 4. Snapshot for tsunami propagation in (a) layer 1 and (b) layer 5. Source: Data Processing, 2026

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Moreover, snapshot modeling was also performed for layer 5 (the detailed layer) to provide a clearer view of the focused research area. This snapshot illustrates how the tsunami reached Pengambengan Village Beach and inundated the land. Figure 4 above explains the process of tsunami generation from the source, which is initiated by a decrease in water level along the coastline, followed by high waves that reach the coastline approximately 37 minutes later. The tsunami waves strike the coast several times before receding and eventually returning to normal conditions within the 3-hour simulation period.

Tsunami Hazard Assessment for Pengambengan Village

The results of the tsunami hazard map created for Pengambengan Village are shown in Figure 5. The tsunami hazard map displays information on the predicted tsunami flow depth and tsunami safe zones, shown by the color on the map and the dashed lines. The map also displays important locations such as residential areas, health facilities, schools, government offices, houses of worship, and evacuation sites. A 200-meter buffer area is also used to determine the tsunami safe zone. In this tsunami hazard map, administrative boundaries up to the *banjar* level are displayed, whereas generally, the boundaries used in this tsunami hazard map are up to the village level, such as Afif & Cipta (2015).

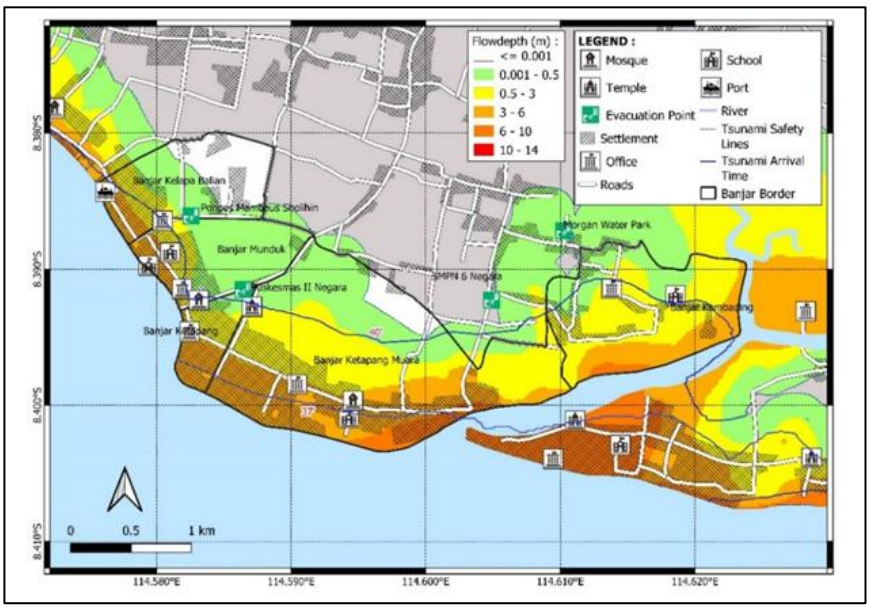


Figure 5. Tsunami hazard map for Pengambengan Village.
Source: Data Processing, 2026

Based on the results of tsunami modeling, it is found that the area affected by tsunami hazards in Pengambengan Village is approximately 91.7 percent of the total area of Pengambengan Village of 5.5 km^2. Then, the estimated maximum flow depth reached between 6 and 10 m in Banjar Ketapang Muara and Banjar Kombanding. For the other 3

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banjars, namely, Banjar Kelapa Balian, Banjar Munduk, and Banjar Ketapang, the maximum flow depth ranges from 3 to 6 m. All five *banjars* in Pengambengan Village were affected by the tsunami. The estimated tsunami arrival time at the Pengambengan coastline is about 37 minutes, as shown in Figure 4. The farthest tsunami inundation to land or the maximum inundation of tsunami waves is 1.6 km.

Determination of Evacuation Site Location

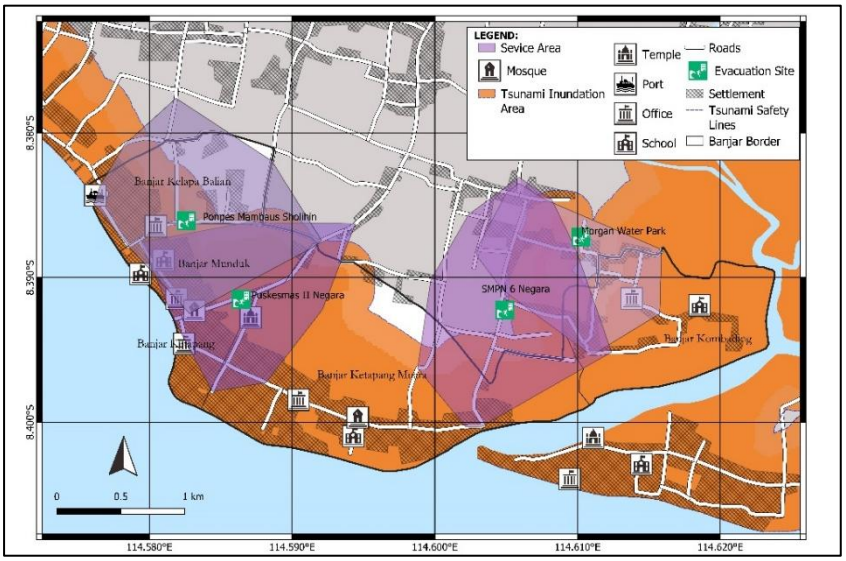


Figure 6. Service area analysis result for evacuation sites in Pengambengan Village. Source: Data Processing, 2026

This study determines the appropriate recommended evacuation sites based on SNI (Indonesian National Standard) rules because Pengambengan Village does not yet have an evacuation site. The evacuation sites proposed in this study fulfill the following criteria: (1) the height of the location or building is higher than the estimated tsunami flow depth; (2) the building is earthquake resistant and far from potential material flow or building collapse; (3) the location is government-owned (public building) or privately owned, but still allowed to be used as an evacuation site (Rahayu & Anita, 2013). Then, to evaluate whether the selected evacuation sites are suitable, a service area analysis was conducted. In this study, we selected four recommended evacuation site locations, namely Ponpes Mambaus Sholihin, Puskesmas II Negara, SMPN 6 Negara, and Morgan Water Park, considering the criteria above. However, two of these sites (SMPN 6 Negara and Morgan Water Park) are located outside Pengambengan Village because no suitable buildings were found in Banjar Ketapang Muara and Banjar Kombanding. All selected sites are situated in areas where the modeled tsunami flow depth is less than or equal to 0.5 meters.

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The service area analysis shown in Figure 6 was used to evaluate the spatial coverage of the selected evacuation sites based on the available physical evacuation time of 24 minutes. The walking speed of elderly individuals, 0.751 m/s, was adopted as a conservative assumption to account for residents with lower mobility. The resulting service areas indicate that four evacuation sites can cover most of the five *banjars* in Pengambengan Village. However, Banjar Ketapang Muara remains inadequately covered, indicating a gap in horizontal evacuation coverage.

Tsunami Evacuation Routes for Pengambengan Village

The shortest route analysis method was performed in this study to determine the shortest evacuation route at seven gathering points spread in Pengambengan Village. The condition and width of the road are also considered in this study, because if the road is in bad condition, the evacuation process will be hampered. The determination of the seven recommended starting points or gathering points was done using the criteria of travel time ≤ 5 minutes from the settlement centroid as described earlier. The selected locations must also be located on main roads and road intersections. These criteria were chosen to represent conditions where people generally spend more time around their homes, and people typically meet at main roads and intersections during evacuation. Each recommended gathering point will generate the shortest evacuation route to one of the four available tsunami evacuation sites, along with the estimated time needed to reach the evacuation site. In this study, seven gathering points were identified, from which seven shortest evacuation routes to the designated evacuation sites were derived. The results of the evacuation routes from the shortest route analysis can be seen from different line colors in Figure 7.

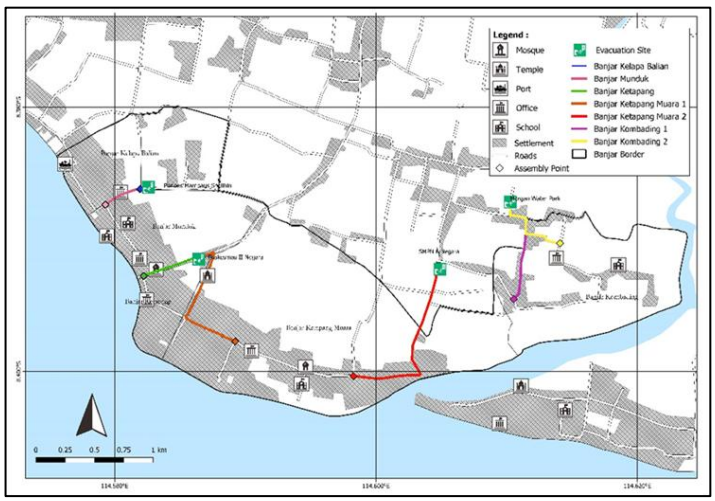


Figure 7. Tsunami evacuation routes in Pengambengan Village.
Source: Data Processing, 2026

The evacuation route for Banjar Kelapa Balian has a distance to the evacuation site at Ponpes Mambaus Sholihin of 72.4 meters with a travel time of 2 minutes, depicted by a blue line. Then, for Banjar Munduk, the distance to the evacuation site is 401.42 meters with a travel time of 9 minutes, depicted by a pink line. The distance for the evacuation route in Banjar Ketapang is 489.7 meters with a travel time of 11 minutes, depicted by a green line. Banjar Kombanding has two evacuation routes with a distance of 955.92 meters and 707.84 meters, and a travel time of 21 and 16 minutes, depicted by purple and yellow lines. Finally, Banjar Ketapang Muara has two evacuation routes with distances of 1222.05 meters and 1519.13 meters, with travel times of 27 minutes and 34 minutes, depicted by orange and red lines. The two evacuation routes from Banjar Ketapang Muara require 27 and 34 minutes, exceeding the available evacuation time of 24 minutes.

The details of travel time and distance for each evacuation route are shown in the Table 2.

Table 2. Travel time and distance of tsunami evacuation.

Location	Evacuation Site	Distance (m)	Travel Time (min) (speed assumption 0.751 m/s)	Building Height Estimation	Flow depth
Banjar Kelapa Balian	Ponpes Mambaus Sholihin	72.4	2	6 m	<= 0.5 m
Banjar Munduk	Ponpes Mambaus Sholihin	401.42	9	6 m	<= 0.5 m
Banjar Ketapang	Puskesmas II Negara	489.7	11	6 m	<= 0.5 m
Banjar Ketapang Muara 1	Puskesmas II Negara	1222.05	27	6 m	<= 0.5 m
Banjar Ketapang Muara 2	SMPN 6 Negara	1519.13	34	6 m	<= 0.5 m
Banjar Kombanding 1	Morgan Water Park	955.92	21	3 m	<= 0.5 m
Banjar Kombanding 2	Morgan Water Park	707.84	16	3 m	<= 0.5 m

Source: Data Processing, 2026

Location of Vertical Evacuation Sites Recommendation

The location of the recommended vertical evacuation sites was also determined in this study using service area analysis. Vertical evacuation sites are considered strategic for low coastal areas that are densely populated and have limited evacuation time (Ferreira et al., 2025). Vertical evacuation facilities have also been implemented or proposed in coastal areas such as Serangan Beach, Kuta Beach, Seminyak Beach, and Tanjung Benoa, suggesting that a similar approach could be considered for Pengambengan Village. The service area is calculated using an estimated evacuation time of 24 minutes from the centroid

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area of Banjar Ketapang Muara. From the service area analysis, it can be seen that vertical evacuation sites can be built within the purple polygon shown in Figure 8.

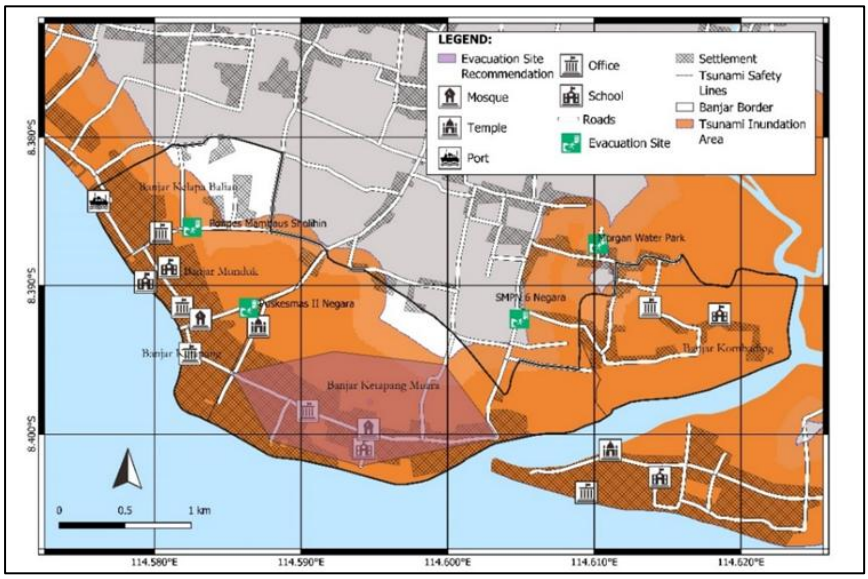


Figure 8. Recommended location of vertical evacuation sites.

Source: Data Processing, 2026

Discussion

The tsunami modeling results indicate that Pengambengan Village is highly exposed to tsunami hazards. The modeled flow depths exceed 2 m across the affected area, indicating a high tsunami hazard level according to Martínez et al. (2017). The highest flow depths, reaching 6–10 m in Banjar Ketapang Muara and Banjar Kombanding, are likely associated with the coastal characteristics of the area and the absence of a substantial green belt to reduce tsunami wave energy. These results are generally consistent with previous assessments that identified Jembrana as an area with high tsunami vulnerability (Sinaga et al., 2011). However, the maximum flow depths obtained in this study are higher than those reported by Kurniawan & Laili (2019).

Because this study uses a scenario-based tsunami model, direct validation against observations from an actual tsunami event at Pengambengan Village was not possible. The modeled results were therefore interpreted as a scenario-based assessment rather than a prediction of a specific future tsunami event. As a consistency check, the results were compared with previous tsunami studies in Bali, as discussed above. The modeled inundation and flow depth patterns are generally consistent with previous assessments that identified Jembrana as a tsunami-prone area, although differences in the maximum flow depth may arise from variations in earthquake source parameters, source location, and model resolution. These comparisons provide supporting evidence for the plausibility of the

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modeled results, while the absence of site-specific observational validation remains a limitation of this study.

The modeled tsunami arrival time at Pengambengan is approximately 37 minutes. This result is within the 30–60 minutes range stated in Bali Governor Regulation No. 34 of 2012 but also highlights the importance of considering local variations in tsunami arrival time. Furthermore, for coastal areas in southern Bali, the modeled tsunami arrival time is significantly shorter, reaching approximately 23 minutes, as shown in Figure 4. Therefore, these findings suggest that the existing guideline may benefit from further evaluation of regional variations in tsunami arrival times, as also highlighted by Hanifa et al. (2022).

The evacuation analysis identified four evacuation sites that can serve most of the five *banjars* in Pengambengan Village. However, Banjar Ketapang Muara remains inadequately covered because no suitable evacuation facility was identified within the area. This limitation is also reflected in the route analysis, where the two proposed evacuation routes from Banjar Ketapang Muara require 27 and 34 minutes, respectively, exceeding the available evacuation time of 24 minutes. Therefore, horizontal evacuation may not be sufficient for all residents in this area. This finding indicates that evacuation planning should consider not only the spatial availability of evacuation facilities but also whether these facilities can be reached within the available evacuation time. A vertical evacuation site is consequently recommended as an alternative, particularly because suitable existing buildings are not available. Before implementation, further assessment of the number of evacuees, shelter capacity, structural safety, and accessibility is required.

The use of a walking speed of 0.751 m/s represents a conservative assumption intended to account for evacuees with lower mobility. Therefore, the travel times obtained in this study should be interpreted as conservative estimates rather than typical travel times for the general population. Although faster walking speeds would reduce travel time, the use of a lower walking speed provides a cautious basis for identifying potential evacuation gaps.

The findings also demonstrate the potential contribution of this study to the Tsunami Ready Program. The resulting hazard map can support Tsunami Ready Indicator 1, while the proposed evacuation sites and routes provide scientific input for Indicator 4. Nevertheless, tsunami evacuation planning should not rely solely on model-based analysis. Community participation and local knowledge remain important for validating evacuation sites, routes, and practical evacuation procedures. The approach presented in this study can

therefore serve as a technical basis to support community-based tsunami preparedness in Pengambengan Village and potentially other coastal areas of western Bali.

Several uncertainties should be considered when interpreting the results. These include uncertainties in earthquake source parameters, including fault geometry, slip distribution, and rupture characteristics, as well as uncertainties associated with bathymetric and topographic data resolution. The evacuation analysis also assumes a constant walking speed and does not account for congestion or variations in human evacuation behavior. Despite these limitations, the results provide a conservative basis for preliminary evacuation planning. Future studies should incorporate higher-resolution datasets, sensitivity analyses, evacuation capacity assessments, and field-based observations of human behavior to improve the realism and reliability of evacuation planning.

D. CONCLUSIONS

This study assessed tsunami hazards and evacuation planning in Pengambengan Village using a worst-case earthquake scenario from the Sumba Megathrust segment. The tsunami hazard analysis indicates that all five *banjars* in Pengambengan Village are affected by tsunami inundation. Approximately 91.7 percent of the village area is affected by tsunami inundation. The maximum flow depth ranges from 6 to 10 m in Banjar Ketapang Muara and Banjar Kombanding, while the estimated tsunami arrival time along the Pengambengan coastline is approximately 37 minutes, with a maximum inundation distance of 1.6 km.

The service area analysis identified four recommended tsunami evacuation sites: Ponpes Mambaus Sholihin, Puskesmas II Negara, SMPN 6 Negara, and Morgan Water Park. However, Banjar Ketapang Muara remains inadequately covered because no suitable evacuation facility was identified within the area. The shortest route analysis identified seven evacuation routes with travel times ranging from 2 to 34 minutes and distances ranging from 72 to 1,519 meters. In particular, the two evacuation routes from Banjar Ketapang Muara require 27 and 34 minutes, exceeding the available evacuation time of 24 minutes.

Based on these findings, a vertical evacuation site is recommended for Banjar Ketapang Muara to address the identified evacuation gap. Further assessment of shelter capacity, structural safety, accessibility, and the number of potential evacuees is required before implementation. Overall, the results provide a scientific basis for supporting tsunami hazard

mapping and evacuation planning in Pengambengan Village and can contribute to the implementation of Tsunami Ready Indicators 1 and 4.

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