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RESEARCH ARTICLE **Open Access**

Evaluating tsunami evacuation routes and shelter capacity using GIS and travel time analysis in Aceh Besar, Indonesia

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Abstract

Tsunamis remain a major hazard for coastal populations, particularly in tectonically active zones such as Indonesia. Strategic evacuation planning plays a critical role in minimizing disaster impacts and improving local resilience. This research focuses on identifying appropriate Temporary Evacuation Stations (TES), Final Evacuation Stations (FES), and accessible evacuation routes within Aceh Besar Regency, utilizing road geometry and estimated travel time as key criteria. Geospatial datasets,including road networks, facility locations, and elevation profiles—were processed using Geographic Information System (GIS) analysis and tsunami inundation modeling. The analysis shows that Neuheun Village contains five TES and four FES, Lamnga hosts one TES, while Baro lacks suitable evacuation infrastructure. Many routes in the study area fall short of standard requirements for width and travel time, especially for pedestrians. Existing TES buildings can accommodate only about 34.52% of the total population. Although motorbikes serve as practical evacuation options, the narrowness of roads limits the use of cars. These findings emphasize the pressing need for additional vertical evacuation shelters and enhancements to road networks to support effective tsunami response strategies.

Keywords: evacuation route; tsunami; earthquake; disaster risk reduction

Introduction

Indonesia is one of the most seismically active countries in the world, as it lies on several active tectonic plates moving at relatively high speeds (Benazir et al., 2016). This geological setting makes the country highly prone to earthquakes and tsunamis. The Indian Ocean earthquake and tsunami in 2004 devastated many regions in western Indonesia, with Aceh Besar Regency being among the most severely affected. The disaster caused severe damage to infrastructure, homes, schools, hospitals, and transportation networks (Urlainis et al., 2022). In Aceh Province, more than 167,000 people lost their lives and hundreds of thousands were injured or displaced (Resosudarmo, 2017). Mesjid Raya Subdistrict, located approximately 0.5 km from the coastline, also suffered major losses. The scale of destruction revealed the lack of tsunami awareness, preparedness, and evacuation planning at the time (Hatthakit & Chaowalit, 2011). The absence of early warning systems and clearly designated evacuation routes further contributed to the high loss of life (Jin & Lin, 2011). These events highlight the urgent need for strategic evacuation planning to mitigate future tsunami risks. Evacuation route planning remains a vital component of disaster risk reduction, aiming to safeguard human lives and property during emergencies.

Two decades after the 2004 Indian Ocean tsunami struck Aceh Province, Indonesia, significant efforts have been made to improve disaster risk reduction, including the development of early warning systems and designated evacuation routes (Lovholt et al., 2014). However, many coastal areas in Aceh Province still lack vertical evacuation shelters, including Mesjid Raya Subdistrict. The absence of such structures has made horizontal evacuation the primary and often the only strategy for tsunami escape in these regions. Certain areas, such as

Mesjid Raya, are geographically advantaged due to their proximity to nearby hills, enabling faster access to natural safe zones.Horizontal tsunami evacuation routes are a key strategy in responding to seismic events that generate tsunamis (Syukri et al., 2016). According to Sea Defense Consultant (2007), several criteria should guide the design of such routes: adequate road width (ideally 6 meters), maximum distance to safety (1 km), clear signage, segregation of pedestrian and vehicle flows, and avoidance of flood-prone or congested areas. These criteria ensure accessibility, efficiency, and safety during evacuation. A summary of these principles highlights the need for clear routes, good road conditions, and suitable escape paths that match the expected number of evacuees.

The National Agency for Disaster Countermeasures (2014) defines Temporary Evacuation Shelters (TES) as prominent structures such as buildings, natural hills, or man-made mounds within tsunami impact zones, designated for immediate evacuation. Final Evacuation Shelters (FES), on the other hand, are public facilities located outside inundation zones, serving as temporary shelters for evacuees for up to two weeks. To determine the suitability of TES, this study used water level maps illustrating anticipated tsunami heights. The term *tsunami run-up* refers to the maximum vertical extent of a tsunami as it moves inland, and it is critical in defining the minimum TES elevation (Fauziah, 2014).

InaSAFE (2017) outlines several criteria for selecting TES, such as a minimum building area of 225 m^2 and access to either primary or secondary roads. Required space per evacuee varies by condition: 0.5 m^2 for standing, 1 m^2 for wheelchair users, and 2.8 m^2 for hospital patients. The Indonesian Tsunami Early Warning System (InaTEWS) estimates tsunami arrival at approximately 40 minutes after an earthquake 5 minutes for alerts, 10 minutes for community response, and 25 minutes for evacuation (Muhajir, 2013).

To ensure timely evacuation, this study also incorporates travel speed data. Evacuee speeds range from 0.751 to 1.5 m/s on foot (Muhajir, 2013; Makalew, 2020), and up to 14 km/h using motorbikes (Mutiawati et al., 2015). These mobility variables are integrated into the spatial analysis to assess whether proposed routes allow sufficient time to reach TES or FES before tsunami arrival.

Previous tsunami evacuation studies have largely focused on urban regions with relatively well-developed infrastructure. However, there is limited attention to semi-rural areas like Mesjid Raya, where road conditions, terrain, and infrastructure vary. Critically, these areas do not yet possess officially designated evacuation route maps issued by the government, making it difficult for residents to know where to go or how to evacuate safely and quickly during a tsunami threat. This gap further increases the vulnerability of coastal communities (Kitamura et al., 2020). Many existing models rely on ideal assumptions, overlooking real constraints such as pedestrian flow, road width, or vertical shelter access.

Building on this gap, the present study seeks to answer a key question: How can suitable evacuation routes and shelter locations be identified in coastal areas with limited infrastructure using spatial, infrastructural, and demographic parameters? To address this, the study develops a model that incorporates tsunami inundation data, vertical shelter requirements, road network geometry, and movement speeds to improve route planning in vulnerable zones like Mesjid Raya. By providing a detailed and location-specific evacuation route model, this research aims to support local governments and disaster management authorities in designing more practical and inclusive preparedness strategies. Ultimately, the study contributes to the broader discourse on tsunami resilience in coastal communities, particularly in developing regions.

Methodology

The focus of this study was on analyzing road networks and identifying potential evacuation points in three villages located within the Mesjid Raya Subdistrict Neuheun, Lamnga, and Baro. These villages are directly adjacent to the Indian Ocean on the western coast of Aceh Besar Regency, making them highly susceptible to tsunami impact. As evidenced during the 2004 Indian Ocean tsunami, this area was severely affected. The combined population of the three villages is approximately 10,296 people, distributed as follows: Lamnga (1,142 residents), Baro (182 residents), and Neuheun (8,972 residents).

To support the evacuation planning process, this study utilized spatial data encompassing the geometry of roads, public buildings, and their respective areas, which were considered as candidate locations for evacuation shelters. A similar service-area based approach was adopted by Sutikno and Murakami (2015) using GIS spatial and network analysis to evaluate tsunami evacuation shelter planning in Pacitan, East Java. Likewise, Bonilauri et al. (2021) developed a GIS-based method for evacuation route mapping on Stromboli Island that incorporated road networks, buildings, and open-space data into evacuation zone and route modelling.

In addition, tsunami inundation height data from Aceh Besar and Banda Aceh documented by Iemura et al. (2008) was incorporated to evaluate vertical safety thresholds. These inundation data were georeferenced and overlaid on digital elevation models to assess whether proposed evacuation shelters met the minimum required elevation.

Further spatial analysis and visualization were supported using GIS software (QGIS), which allowed the integration of building footprints, road geometry, and hazard layers. This approach is consistent with studies modelling tsunami induced evacuations that integrate such spatial datasets (Li et al., 2019). The combined datasets were used to assess accessibility, travel time, and suitability of road segments and evacuation shelters, where evacuation modelling relies on shortest-path calculations of built environments (Melo et al., 2020). The research methodology applied in this study is summarized in Figure 1, which presents a detailed flowchart of the research steps conducted.

Determination of Evacuation Points (TES and FES)

The selection of TES and FES was guided by several physical and functional criteria. For TES, buildings were required to have a height above the predicted tsunami inundation level and a minimum floor area of 225 m². Their capacity was assessed by dividing the total building area by the space requirement per person 0.5 m² for individuals in a standing position. For FES, as per the guidelines of the BNPB (2014), additional criteria were applied: the structure must be located outside the tsunami-affected zone, have sufficient space for emergency shelters or tents, allow for the establishment of a temporary kitchen, and have access to clean water. The condition of being outside hazard zones aligns with findings in vertical evacuation modeling studies, which emphasize locating shelters in safe areas to minimize risk and evacuation time (Sun et al., 2022). Moreover, the requirement for minimum living standards including proper sheltering space and basic facility support is consistent with recommendations in the literature addressing best practices for evacuation centres (Kako et al., 2020).

To obtain the building area measurements, this study used Google Earth Pro software. The process involved identifying potential buildings through high-resolution satellite imagery, followed by the use of the polygon measuring tool to manually trace the perimeter of each structure. The software then calculated the enclosed area in square meters, which was recorded and used to evaluate whether the buildings met the minimum area requirement. This approach enabled consistent spatial data collection, particularly in areas where on-site surveys were not feasible.

Determination of Road Segments for Evacuation Routes

The selection of road segments for tsunami evacuation was guided by specific thresholds for both road width and travel time. These criteria were established to ensure that evacuees can move safely and efficiently under emergency conditions. For road width, a minimum of 4 meters was set for environmental or residential roads, and 6 meters for arterial roads. These standards reflect common planning regulations and were selected to accommodate bidirectional movement, especially for pedestrians and motorbikes (Mutiawati et al., 2022).

In terms of travel time, a maximum of 35 minutes was set based on the tsunami warning window provided by the Indonesian Tsunami Early Warning System (InaTEWS), which estimates approximately 40 minutes from earthquake occurrence to tsunami arrival. This includes 5 minutes for decision-making and alert issuance, leaving 35 minutes for evacuation. Travel speeds were assumed to be 14 km/h for motorized vehicles (Kiichiro, 2013) and 2.704 km/h for pedestrians. These parameters were used in network analysis to define accessible zones within the critical evacuation window.

All spatial inputs including road segments, building locations, and inundation zones were integrated within the GIS environment. The final output consisted of evacuation maps that identified viable TES and FES, along with optimal evacuation routes that reflect physical constraints and time limitations.

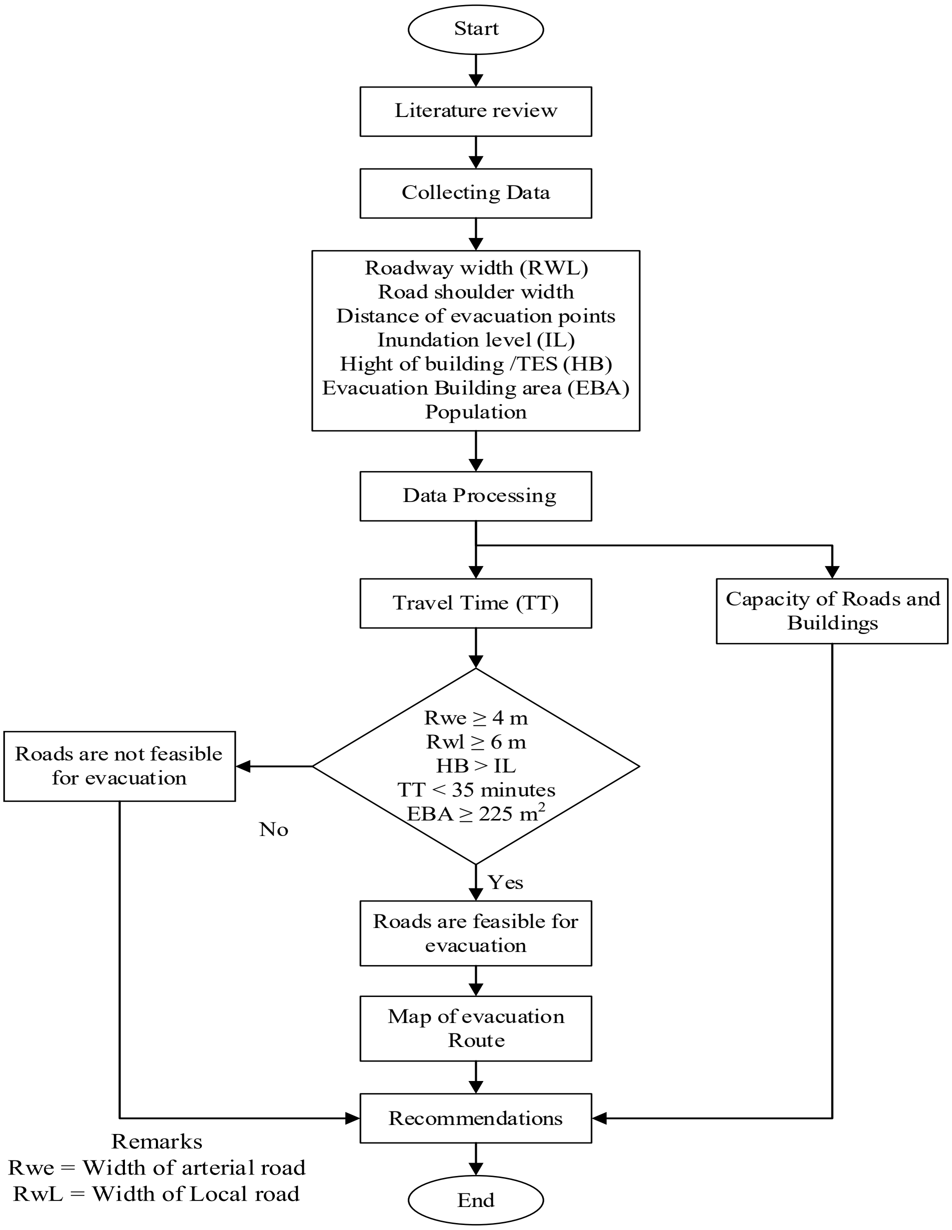

Figure 1. Flowchart of the research methodology.

Results

Evacuation Shelters

Evacuation shelters play a critical role in reducing fatalities of tsunami events by providing safe refuge during and after the occurrence of a tsunami (Sotelo-Salas, C., et al., 2024). Based on their function and structure, shelters generally classified into two categories: temporary shelters and final or permanent shelters (Shibayama, T., et al., 2013). Temporary shelters typically include easily accessible open spaces or public buildings such as schools or mosques, which serve as initial gathering points immediately after a tsunami warning is issued (Hasan, M., 2024). In contrast, final evacuation shelters are specifically designed and engineered to withstand tsunami forces. These often take the form of vertical evacuation structures, such as multi-story reinforced buildings or towers, intended to accommodate evacuees who cannot reach natural high ground in time.

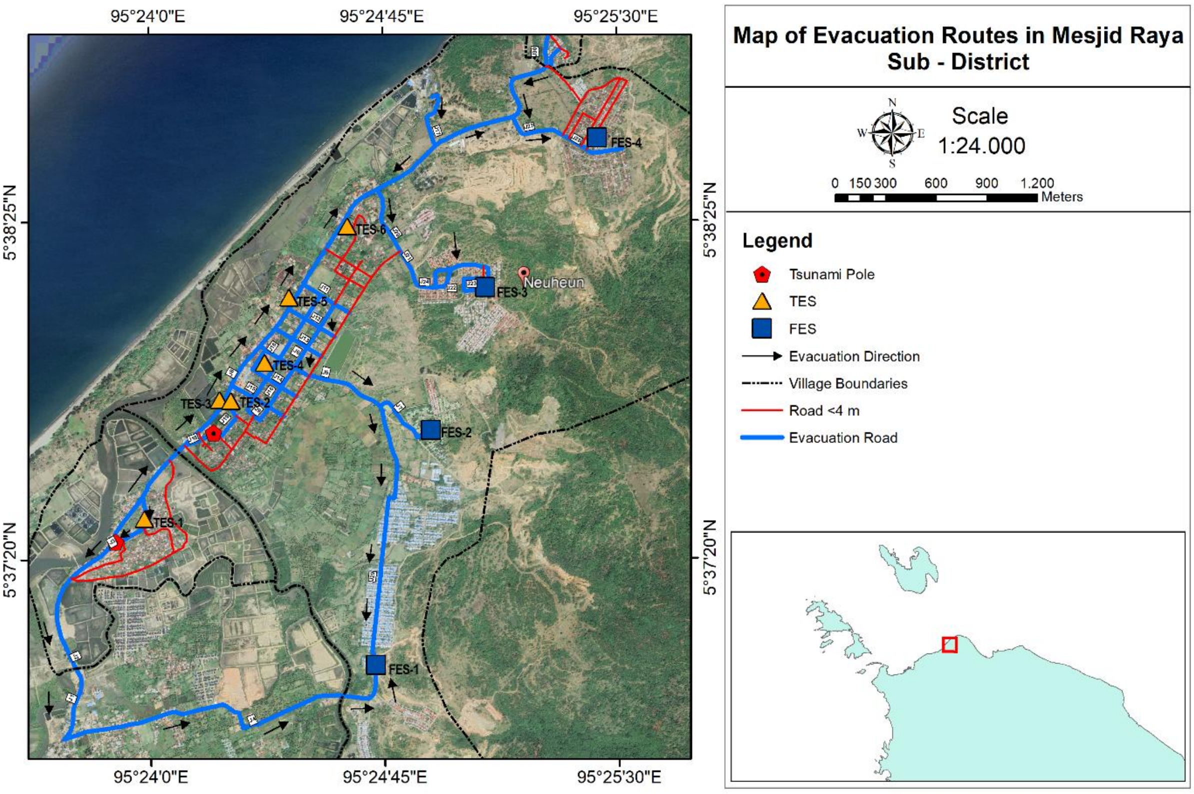

Figure 2. Map of evacuation TES and FES in Mesjid Raya Sub-District.

Figure 2 presents a spatial overview of the study area, illustrating the distribution of Temporary Evacuation Shelters (TES), Final Evacuation Shelters (FES), and the evacuation routes that connect them. Within the study area, six buildings have been designated as TES facilities, consisting of both two-storey and three-storey structures. In addition, four sites were identified as suitable for FES. The spatial distribution of these shelters is uneven, with the majority concentrated in Neuheun Village. The accommodation capacity of each TES was estimated based on a standard of 0.5 m² per person in a standing condition, resulting in a combined capacity of approximately 3,554 individuals across the six designated buildings. In contrast, the total population of the three villages within the study area is 10,296 people (BPS, 2020). This discrepancy indicates that the available TES facilities can accommodate only about 34.52% of the population. Further details regarding the selected vertical evacuation buildings and their respective capacities are summarized in Table 1.

Table 1. Temporary evacuation shelters in the study areas.

No	Name of Vertical Evacuation	Location	Area (m^2)	TG > TR (m)	Approximate capacity (person)
1	Jami' Al-Mahabbah Mesjid Mosque (two-storey)/**(TES-1)**	Lamnga Village	563	5 > 4,0	(563*1)/0.5 =1126
2	School (SDN) Neuheun (two-storey)/**(TES-2)**	Neuheun Village	*135	4 > 3,4	(135*1)/0.5 = 270
3	House (three-storey)/**(TES-3)**	Neuheun Village	258	7,5 > 3,4	(258*2)/0.5 =1032
4	Office of State Electricity (two-storey) / **(TES-4)**	Neuheun Village	1007	4 > 3,4	(1007*1)/0.5 =2014
5	Shops (three-storey)/**TES-5)**	Neuheun Village	*172	7 > 3,4	(172*2)/0.5 = 344
6	School (SMKN 1) Mesjid Raya (three-storey)/**(TES-6)**	Neuheun Village	391	4 > 3,4	(391*1)/0.5 = 782

Remarks:
* It is suitable based on the height of the building but not feasible in terms of area (min. 225 m^2); TG = Building height; TR = 2004 Tsunami run-up height

The results demonstrate that although these six shelters collectively provide space for 3,554 persons, this represents only one-third of the exposed population, leaving more than 6,700 residents without access to safe refuge. This imbalance between demand and supply highlights a significant vulnerability in community evacuation readiness. In practice, such capacity shortfalls may lead to overcrowding, delayed evacuation, or the exclusion of at-risk groups, particularly in densely populated areas of Neuheun Village. Similar findings were reported by Shibayama et al. (2013), who noted that insufficient vertical shelter capacity undermines the effectiveness of tsunami evacuation strategies.

The elevation criteria shown in Table 1 confirm that the selected TES buildings are located above the 2004 tsunami run-up height, ensuring structural safety. However, the area limitation of two buildings (TES-2 and TES-5) suggests that not all designated shelters meet both height and minimum area standards, raising questions about their feasibility during an actual event. These results underscore the urgent need for either expanding the current TES facilities or incorporating alternative safe zones in evacuation planning.

Beyond structural shelters, tsunami monuments also play a critical role in preparedness and evacuation planning. These monuments, which record the 2004 tsunami run-up heights, provide visual references that help communities recognize safe elevation thresholds and understand the extent of past tsunami impacts. In the study area, monuments are located at Krueng Raya Road (Lamnga Village, 4.0 m, 1.50 km from the coastline) and Meunasah Neuheun (Neuheun Village, 3.40 m, 1.30 km from the coastline), serving as practical markers for identifying appropriate temporary gathering points.

In addition to TES, four Final Evacuation Shelters (FES) were identified in Neuheun Village. Their characteristics and suitability, based on BNPB (2014) criteria, are presented in Table 2.

Table 2. Final Evacuation Shelters (FES).

No	Final Evacuation Shelter	Height (MASL)	Located Outside the Tsunami Area	Have a Food Preparation Area	Have Access to Clean Water
1	Cinta Kasih Residence (Neuheun Village) / **(FES-1)**	16	√	√	√
2	Nurani Dunia Residence (Neuheun Village) / **(FES-2)**	13	√	√	√
3	Jackie Chan Residence (Neuheun Village) / **(FES-3)**	95	√	√	√
4	Ujong Batee Residence (Neuheun Village) **(FES-4)**	37	√	√	√

Table 2 shows that all four FES are located outside the tsunami hazard zone at safe elevations ranging from 13 to 95 m above sea level. Unlike TES, these facilities are equipped with food preparation areas and reliable access to clean water, making them suitable for sustaining evacuees over extended periods.

This distinction is crucial, as TES (Table 1) can only accommodate about one-third of the exposed population. FES therefore complement TES by functioning as long-term safe havens, consistent with BNPB (2014) guidelines that emphasize both immediate safety and logistical sustainability.

However, the spatial concentration of all FES in Neuheun Village presents accessibility challenges for residents in Lamnga and Baro, who would require longer travel times to reach these shelters. This imbalance reflects a broader challenge in rural evacuation planning, where uneven shelter distribution can exacerbate vulnerability (Afandi, 2022; Shibayama et al., 2013). Addressing such inequities is essential to ensure that evacuation strategies are both effective and inclusive.

Feasibility of Evacuation Routes Based on Road Width and Travel Time

The road geometry survey revealed that many road segments in Neuheun, Lamnga, and Baro villages fall below the minimum width requirement for tsunami evacuation routes (4 m), as specified by the Sea Defences Consultant. According to Afandi (2022), the minimum standards are 2.2 m for vehicles and 1 m for pedestrians. Road lengths were digitized in ArcGIS to determine travel distances from origin points to TES and FES, forming the basis for subsequent travel time analysis Table 3 presents the road segments that meet the minimum standards for tsunami evacuation routes in the three study villages. Most of the listed roads have widths between 4 and 7 meters, which allows for mixed pedestrian and vehicular flows during evacuation. The presence of arterial roads such as Laksamana Malahayati segments ensures faster connectivity to TES and FES, while local roads provide essential access within residential areas. However, several routes (e.g., J12 and J11) only marginally satisfy the minimum requirement or are in poor pavement condition, which may cause bottlenecks and delays during mass movement.

Table 3. The roads suitable for evacuation routes in the three villages.

No	Streets	Width (meter)	Distance (meter)	Pavement Type	Condition	Road Type
1	*Laksamana Malahayati Segmen 1 (J2)	7	1460.53	FP/(Flexible Pavement)	Good	Arterial
2	*Mesjid (J3)	4	406.45	FP	Good	Local
3	**Laksamana Malahayati Segmen 1 (J8)	7	3243.05	FP	Good	Arterial

No	Streets	Width (meter)	Distance (meter)	Pavement Type	Condition	Road Type
4	**J18	4.3	217.48	FP	Good	Local
5	**J19	4	264.68	FP	Good	Local
6	**J9	4	101.97	FP	Good	Local
7	**J10	4.5	773.29	FP	Good	Local
8	**J15	4.9	351.16	FP	Good	Local
9	**J14	4.55	302.96	FP	Good	Local
10	**J6	5	338.99	FP	Good	Local
11	**J13	4.74	317.86	FP	Good	Local
12	**J12	4.13	307.2	FP	Poor	Local
13	**J11	3.73-4.5	314.71	FP	Good	Local
14	**J16	4.1	752.7	FP	Good	Local
15	**Balai Perikanan (J17)	4.15	407.3	FP	Good	Local
16	**Lr. Teguk Seunehi (J20)	5.6	321.37	FP	Good	Local
17	**Utama (J21)	7.9	935.48	RP (Rigid Pavement)	Good	Local
18	**Durian (J24)	4.72	179.98	RP	Good	Local
19	**G. Geurudoeng (J25)	4	203.78	RP	Good	Local
20	**J23	4	138.65	RP	Good	Local
21	**J5	4.2	1018.76	FP	Good	Local
22	**Imam (J7)	4	374.27	FP	Good	Local
23	**Malahayati KM 15 (J29)	5.7	901.87	PB (Paving Block)	Good	Local
24	**Perumahan (J27)	4.7	361.56	FP	Good	Local
25	**J22	4	69.85	RP	Good	Local
26	**Lumba-lumba (J28)	4	354.74	FP	Good	Local
27	***Laksamana Malahayati Segmen 1 (J30)	7	190.87	FP	Good	Arterial
28	***Laksamana Malahayati Segmen 2 (J26)	4	138.97	FP	Good	Local
29	****Laksamana Malahayati Segmen 1 (J1)	7	403.49	FP	Good	Arterial
30	****Labuy (J4)	4.4	2024.08	FP	Good	Local

Remarks: *Lamnga Village; **Neuheun Village; ***Baro Village; ****Out of the Study Areas.

These findings highlight that while physical infrastructure exists to support evacuation, variations in road width, pavement condition, and functional hierarchy could significantly influence evacuation speed and safety. In Neuheun Village, where population density is highest, the prevalence of narrow local roads increases the risk of congestion, making it difficult to meet the tsunami arrival time threshold. This aligns with Afandi (2022), who emphasized that inadequate road geometry is a critical factor limiting evacuation efficiency in coastal settlements.

When integrated with travel time analysis (Figures 3–5), these results provide a more comprehensive understanding of evacuation feasibility. They underscore that road geometry alone is insufficient without considering time constraints, settlement density, and the accessibility of TES and FES.

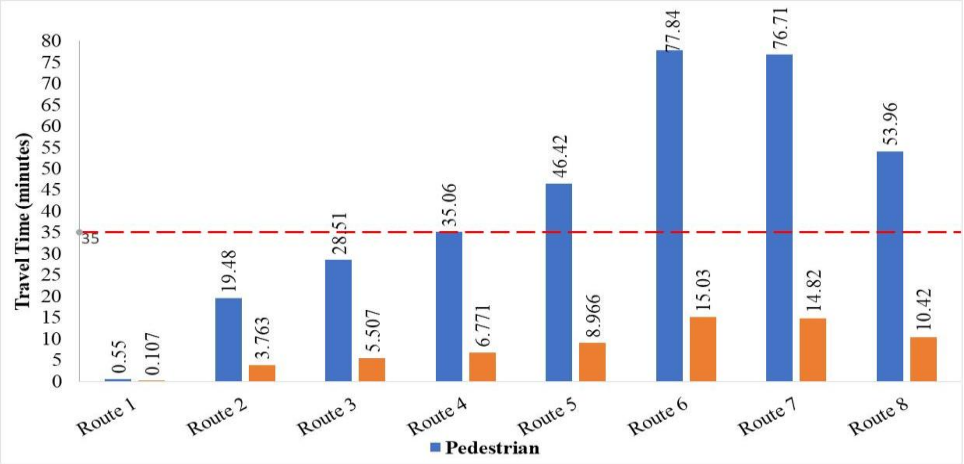

Figure 3. Travel time of evacuation routes in Lamnga Village.

Figure 3 shows the estimated travel times in Lamnga Village. Most motorcycle routes are well below the 35 minute threshold, indicating safe evacuation feasibility. However, several pedestrian routes particularly Routes 5, 6, 7, and 8 exceed this limit, suggesting constraints for residents traveling on foot from peripheral areas.

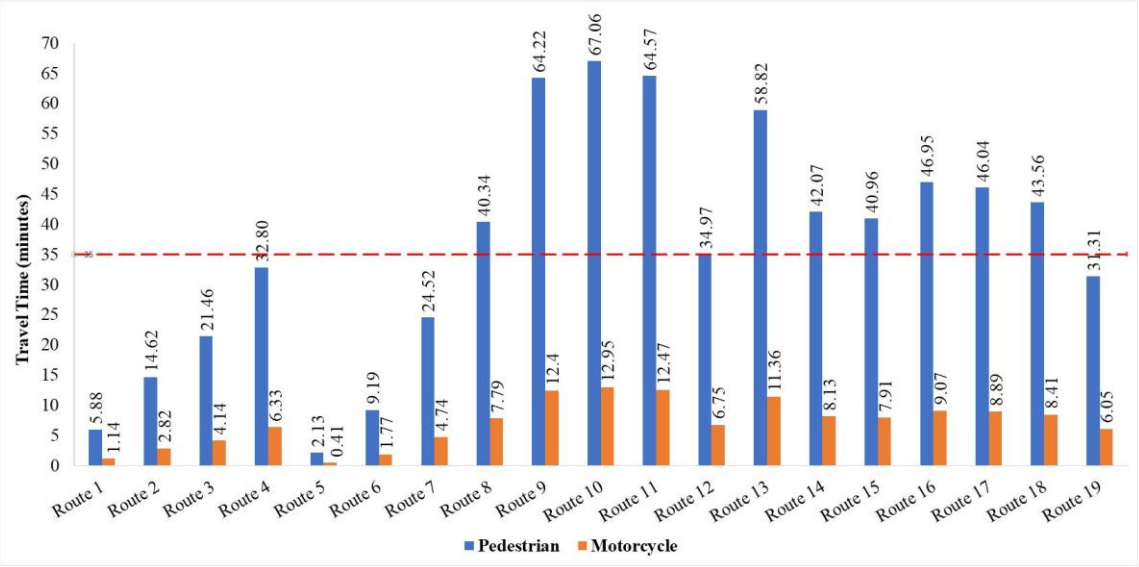

Figure 4. Travel time of evacuation routes in Neuheun Village.

In contrast, Figure 4 illustrates Neuheun Village, where narrow local roads and high population density create congestion risks. Several pedestrian routes exceed the 35 minute threshold, raising serious concerns about the ability of residents to evacuate before tsunami arrival.

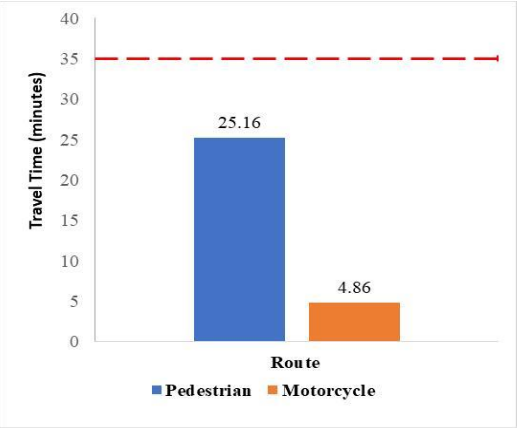

Figure 5. Travel time of evacuation routes in Baro Village.

Figure 5 shows Baro Village, where evacuation routes are relatively shorter and less congested. Motorcycles achieve very fast evacuation times (around 5 minutes), while pedestrians require about 25 minutes, still under the 35-minute safety threshold. This indicates that Baro is comparatively safer than Neuheun.

Discussion

This significant shortfall in evacuation capacity poses a serious risk during tsunami events. The limited availability of safe shelters was a contributing factor to the high number of casualties during the 2004 tsunami. In such scenarios, overcrowding or the inability to reach a safe location in time can result in fatal consequences. Addressing this gap is therefore critical. Increasing the number of well-distributed and structurally resilient evacuation buildings in tsunami-prone areas could substantially enhance community preparedness and reduce potential loss of life (Hamouda et al., 2024; Jitt-Aer et al., 2022; Perera et al., 2022; Harnantyari et al., 2020).

The effectiveness of evacuation shelters depends on several factors, including their elevation relative to the projected tsunami inundation level, structural integrity to resist seismic and hydrodynamic loads, adequate capacity to accommodate the exposed population, and accessibility within the limited time frame between warning issuance and wave arrival (Kako et al., 2020). According to the Intergovernmental Oceanographic Commission (2008), shelters should ideally be located at elevations exceeding the predicted inundation height typically above 4 meters in many Acehnese coastal zones and should be reachable within 15 minutes on foot to ensure timely evacuation (Sotelo-Salas et al., 2024). The absence of permanent shelters increases the likelihood of delayed evacuation and higher casualties, particularly during nighttime or adverse weather conditions. Developing robust, multi-functional vertical evacuation shelters therefore remains a crucial yet underprioritized element of disaster risk reduction in vulnerable regions.

Evacuation route performance is determined by both physical and behavioral factors, such as road width and travel time (Fathianpour et al., 2024). Roads that are sufficiently wide typically at least 4 meters can support both pedestrian and vehicular movement, allowing for bidirectional flow and reducing the likelihood of congestion. In contrast, narrow pathways and alleyways, especially those under 2 meters, often become bottlenecks that slow down evacuation and increase the risk of fatal delays (Takabatake et al., 2022).

Kramarova (2021) and Mutiawati (2022) emphasized that the minimum road width required is 0.85 m for pedestrians and 2.1 m for two motorcycles traveling side by side. Evacuation by cars is not recommended due to the wider road requirements. Thus, the total minimum road width suggested is 3.8 m, consisting of 1.7 m for pedestrians and 2.1 m for motorcycles. Afandi (2022), however, recommended a slightly higher minimum of 4.2

m. To improve evacuation performance, it is advisable not to rely on the bare minimum but to implement road widening where possible.

Travel time is another crucial factor in the effectiveness of tsunami evacuation (Chen et al., 2022). Studies employing Geographic Information System (GIS) network analysis have shown that under optimal conditions, evacuation on foot over a distance of 800 meters can be completed in less than seven minutes (Di Mauro et al., 2013). However, when road conditions, terrain, and potential congestion are considered, actual evacuation times often exceed safe thresholds. Simulation models from tsunami-prone cities in Japan, such as Kamakura, Zushi, and Fujisawa, suggest that even small delays caused by road obstructions can lead to higher mortality rates (Takabatake et al., 2022).

The Estimated Time of Arrival (ETA) of a tsunami refers to the interval between the triggering earthquake and the moment the waves are expected to reach the coastline. This measure is critical for assessing evacuation feasibility based on available travel time. In Banda Aceh, the ETA is estimated at 35 minutes (Syamsidik et al., 2019), indicating that residents in tsunami-prone areas must evacuate within that timeframe. However, ETA varies by location. For example, in Padang, the estimated tsunami arrival time ranges from 20 to 30 minutes (Ashar, 2018), highlighting the importance of location-specific evacuation planning.

In the case study areas, evacuation feasibility varied significantly. In Lamnga Village, although one TES exists, several pedestrian routes exceed the 35-minute ETA, indicating partial infeasibility for those evacuating on foot. In Neuheun Village, five TESs and four FESs are available; however, many pedestrian routes also surpass the ETA threshold due to narrow and congested road networks, highlighting that shelter availability alone does not guarantee accessibility. In contrast, Baro Village lacks both TES and FES, yet most evacuation routes remain under 35 minutes for both pedestrians and motorcycles, making it relatively safer in terms of travel time but vulnerable due to the absence of designated shelters.

Infeasible evacuation routes, particularly for pedestrians, pose serious risks during tsunami events. When routes are too long, obstructed, or pass-through hazardous areas, they can significantly hinder the ability of individuals especially the elderly, children, and people with disabilities to reach safe zones within the limited time available. As a result, these vulnerable groups face a heightened risk of injury or death.

During an actual tsunami event, delayed or unsuccessful evacuation due to poorly planned routes can result in mass casualties, particularly in densely populated or low-lying coastal areas. The consequences are even more severe when vertical evacuation buildings are insufficient or inaccessible by foot. Therefore, identifying and mitigating infeasible routes is essential in disaster preparedness planning.

These findings suggest that evacuation strategies must be context-specific. In Lamnga, improving pedestrian accessibility and constructing additional TES is critical. In Neuheun, widening key bottleneck roads and ensuring faster pedestrian access to shelters should be prioritized. In Baro, the absence of TES and FES is the most urgent issue despite favorable travel times, requiring the establishment of new vertical evacuation structures to ensure safety in case of road blockages or delayed evacuation.

Effective evacuation planning must prioritize pedestrian accessibility by ensuring routes are short, direct, and free of physical barriers. It should also include the development of additional vertical evacuation structures in strategic locations and the implementation of clear signage and community-based drills. Addressing these challenges not only improves evacuation strategies but also enhances the overall resilience of at-risk communities.

Conclusion

The findings of this study emphasize the urgent need to enhance evacuation infrastructure and planning in tsunami-prone areas. In Lamnga Village, only one Temporary Evacuation Shelter (TES) was identified, while several pedestrian routes exceed the 35-minute Estimated Time of Arrival (ETA), showing limited effectiveness. Neuheun

Village, with five TESs and four Final Evacuation Shelters (FESs), offers more facilities, yet many pedestrian routes still far exceed the time threshold due to narrow roads and dense settlements, making evacuation particularly challenging. In contrast, Baro Village lacks both TES and FES, but most evacuation routes both pedestrian and motorcycle remain feasible within the 35-minute ETA, rendering it relatively safer in terms of evacuation time but less resilient due to insufficient shelter provision.

Regarding supporting infrastructure, only two evacuation roads in Lamnga and Baro Villages and 24 roads in Neuheun Village meet the minimum four-meter width standard. Although road access exists, evacuation performance is strongly constrained by settlement density and route geometry. Dependence on motorcycle evacuation also poses risks, especially for vulnerable groups such as the elderly, children, and persons with disabilities.

To address these challenges, it is essential to expand the number and capacity of vertical evacuation shelters, particularly in Lamnga and Baro, while improving accessibility in Neuheun. Road infrastructure should be upgraded especially substandard routes to ensure safer alternatives during mass evacuation. These physical measures must be reinforced by community-based preparedness, including clear signage, regular drills, and reliable early warning systems. Future research should examine community evacuation behavior, scenario-based tsunami simulations, and the integration of geospatial analysis with mobile alert systems for real-time evacuation planning. Such efforts will provide a more comprehensive basis for disaster risk reduction and strengthen the resilience of coastal communities.

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