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ANALYSIS OF TIME AND DISTANCE FACTORS IN TSUNAMI EVACUATION TRANSPORTATION PLANNING IN PADANG, WEST SUMATRA

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ABSTRACT: Based on the tsunami-prone zone map of Padang City, the Padang Barat sub-district is categorized as a High-Risk Zone. A tsunami in Padang City is predicted to occur within 20–30 minutes after a large-scale earthquake; therefore, it is necessary to analyze the distance and time parameters involved in the evacuation process to help residents estimate their ability to save themselves in the event of a tsunami. The research results identified 10 potential shelters in the Padang Barat sub-district, followed by an analysis of the time and distance parameters from the shoreline to each potential shelter. Based on the analysis, the fastest estimated time of arrival (ETA) is to the STBA Prayoga shelter, with a travel time of 2 minutes 30 seconds from the shoreline, while the longest ETA is to the SMPN 2 Padang shelter, with a travel time of 10 minutes 17 seconds. In the final stage, questionnaires were distributed throughout the Padang Barat sub-district. The analysis revealed that residents demonstrated good understanding and preparedness for evacuation during disasters. The Experience Indicator showed an achievement of 60.4%, the Knowledge Indicator was at 83.4%, and the Implementation Indicator stood at 59.5%. Although the Implementation Indicator was the lowest, overall, the community was considered well-prepared to face earthquake and tsunami threats.

Keywords: Mitigation, ETA, Tsunami, Shelter, Tsunami Risk Zone

1. INTRODUCTION

The city of Padang is one of the cities in Indonesia that are vulnerable to natural disasters such as earthquakes and tsunamis, due to its location at the collision zone between two major tectonic plates: the Indo-Australian Plate to the south and the Eurasian Plate to the north [1]. This region is characterized by the presence of a tectonic earthquake centre located around the Mentawai Islands Regency. The collision between the Indo-Australian Plate and the Eurasian Plate occurs at a rate of approximately 50–70 mm per year, serving as the primary trigger for seismic activity in the subduction zone [2].

The location of Padang City, situated on the west coast of Sumatra, directly bordering the open sea (Indian Ocean) and an active collision zone of two tectonic plates, makes Padang one of the cities most vulnerable to tsunami hazards [3]. After the tsunami hit Aceh in 2004 (Indian Ocean tsunami), Padang's readiness for disasters gained international attention, as the region was expected to face seismic and tsunami hazards [4]. The potential impact of the tsunami that hit Padang is estimated to be significant because of the large population living in coastal areas. The main reason for this density is that the main economic activities in Padang, including critical infrastructure, health services, schools, public offices, and transportation networks, are built parallel to the coastline. This multiplies the population's exposure to potential tsunami waves [5]. The vulnerability of coastal areas to natural disasters is increasing as population concentration increases, making coastal areas the center of economic activity and densely populated cities [6]. Based on history, earthquakes accompanied by tsunamis in Padang City occurred in 1797 and 1833, causing only a few fatalities, but the height of the tsunami waves is estimated to have reached 5 to 10 meters [7].

Padang City is divided into three tsunami hazard zones: High Risk Zone, Medium Risk Zone, and Low Risk Zone [8]. The High Risk Zone refers to areas with high vulnerability to tsunamis. One of the sub-districts located in the High Risk Zone is the West Padang sub-district, which has an area of 7.00 km² and a population density of approximately 6,137 people per km² [9].

To reach a safe place, residents have to walk 3-5 km to escape to a safe place [10]. The tsunami evacuation time in Padang City can be said to be short; therefore, the choice of vertical evacuation is urgent compared to walking along a safe area. So, building shelters that minimize the impact of disasters is one of the disaster resilience strategies [11]. Padang City, which is on the west coast of Sumatra, has a high risk of being affected by the tsunami, so the government is trying to build and provide evacuation places, both permanent and temporary [12]. However, in the West Padang sub-district, no official shelters have been built; only some buildings could be used as potential shelters. Based on research conducted by [13], 23 buildings were found that had the potential to become TES, 10 of which were in the West Padang sub-district.

To reduce the impact of disaster-related losses, disaster management efforts are essential. According to the Law of the Republic of Indonesia No. 24 of 2007, disaster management is a dynamic, continuous, and integrated process aimed at improving the quality of activities related to disaster observation, analysis, prevention, mitigation, preparedness, early warning, emergency response, rehabilitation, and reconstruction [14]. Planning evacuation routes and evacuation shelters is part of the tsunami disaster mitigation phase. Disaster mitigation involves a series of efforts to reduce disaster risk through physical development as well as through awareness-raising and capacity-building initiatives to face potential threats. During the evacuation process, time and accessibility are critical factors. Several methods are employed in disaster risk reduction, including the provision of evacuation route maps, shelters, and directional signs, also technically using Ground Penetrating Radar (GPR) for making decisions on the prone zone to be avoided [15]. The mitigation phase refers to actions taken both before and after a disaster to minimize its impact [16]. Disaster management is a major responsibility that is not confined to specific locations, nor does its importance diminish once the immediate threat has passed.

The evacuation time in Padang City after the occurrence of a major earthquake is around 20–30 minutes [17]. With that estimated evacuation time, it is estimated that the people of the West Padang sub-district will not reach a safe place if they evacuate by horizontal evacuation. Therefore, this research will calculate the time needed for the community to reach potential shelters in Padang Barat sub-district and measure how the community understands the implementation of disaster mitigation.

In relation to the focus on evacuation planning in Padang, previous studies have also examined evacuation strategies in disaster-prone areas such as Mount Marapi. These studies developed evacuation models by incorporating several key variables, including distance from the crater, elevation, proximity to hot springs, land cover, river proximity, slope gradient, and wind direction. These factors were utilized to identify safe and effective evacuation routes. Accurate prediction of ashfall distribution is crucial for safeguarding populations located downwind of the volcano [18]. Another study employed a large-scale stochastic evaluation method to assess human impact. The findings revealed that pedestrian congestion significantly increased casualty rates, even in communities with high disaster awareness, due to reduced walking speeds. Additionally, building damage and structural collapse contributed to longer evacuation times and heightened flood risks**.** Tsunami simulation and evacuation were used to determine preventive measures to reduce human casualties [19].

Takahashi, Yasufuku, and Abe also conducted a study on evacuation scenarios in 2021. The study revealed that obstacles along evacuation routes, particularly those that force evacuees to use stairways, significantly impede evacuation flow, resulting in delays of more than 1.5 times compared to unobstructed scenarios. These findings highlight the importance of establishing alternative evacuation routes and implementing strategies to redirect evacuees away from congested areas, thereby enhancing overall evacuation safety.

Evacuation dynamics are complex and influenced by various factors; for instance, during tsunami evacuations, street blockage from earthquake-induced building damage can impede evacuees' walking speed, increasing casualties. The degree of congestion, often measured by the number of people per sidewalk area, also plays a critical role in determining walking speed. Similarly, in underground facilities, obstacles such as blocked corridors or stairways can delay evacuation, particularly when people are concentrated on stairs.

In contrast, research on flooding and landslides in Thailand indicates that evacuation time is affected by whether evacuees are grouped or ungrouped and the number and speed of available vehicles. Ultimately, employing trip assignment models and optimization techniques can aid in identifying effective evacuation routes [20].

Evacuation scenarios are complex and influenced by factors ranging from infrastructure damage to human behavior. In tsunami evacuations, for example, street blockages caused by earthquake damage can reduce evacuees' walking speeds, thereby increasing casualties. The degree of congestion, defined by the number of people per sidewalk area, also significantly impacts walking speed. Furthermore, tsunami hazard assessments indicate that areas like Padang, Indonesia, face the threat of substantial tsunamis, underscoring the importance of effective evacuation strategies, although horizontal evacuation methods have been deemed ineffective for some segments of the population. In underground facilities, evacuation times can increase due to obstacles that cause congestion, particularly on stairways, with blocked corridors having a more severe impact than blocked staircases. To address these challenges, mathematical models and trip assignment models are essential tools for analyzing and optimizing evacuation routes, taking into account factors such as vehicle availability and evacuee grouping. It is also important to recognize that evacuation behavior can vary by region, as demonstrated by the diverse responses observed during the Great East Japan Earthquake.

All previous research resulted in the models offering a proactive approach to disaster management, enabling authorities to prepare for various eruption scenarios. By understanding the interplay of these variables, evacuation plans can be optimized for efficiency and safety. The goal is to minimize risks to human life and property by facilitating timely and organized evacuations. This research contributes to the development of robust strategies for mitigating the destructive effects of volcanic eruptions. Furthermore, the findings are intended to enhance community resilience and preparedness in the face of natural disasters. The integration of local knowledge and scientific modeling can lead to more effective evacuation strategies. Ultimately, this research aims to safeguard the communities surrounding Mount Marapi by providing data-driven evacuation plans. The models can be regularly updated with new data to maintain their accuracy and relevance. This ongoing process of refinement ensures that evacuation plans remain effective in the face of evolving volcanic activity. In conclusion, the development of precise evacuation models is crucial for protecting lives and mitigating the impact of volcanic eruptions.

2. RESEARCH SIGNIFICANCE

Understanding the dangers of earthquakes and tsunamis is crucial to reducing their impacts. The tsunami disaster has been considered a major threat, leading to extensive research aimed at assessing the vulnerability and risk of coastal areas. Tsunami risk assessments have been conducted to estimate the potential damage and losses that could occur in affected regions. Padang City, particularly the West Padang sub-district, is highly vulnerable to tsunami disasters. Therefore, this study provides an overview of the distance and time required for evacuation, particularly vertical evacuation, in the West Padang sub-district. It also highlights how local communities apply their knowledge of evacuation procedures as a form of disaster mitigation. The findings of this study offer valuable insights for local governments, assisting in the formulation of policies for both structural and non-structural mitigation efforts related to earthquake and tsunami disasters. Additionally, the research examines variables such as population density, building quality, and accessibility to evacuation routes—factors that significantly influence the success of evacuation procedures.

3. METHODS

This research is a quantitative study with a descriptive case study approach, aimed at exploring the community's understanding of mitigation measures for earthquake and tsunami disasters. The study uses numerical data to examine disaster preparedness. The research subjects are the residents of the West Padang sub-district, who are considered to be at risk of tsunami impacts. They are living in the red zone. The data collection stages are outlined as follows:

3.1 Parameter Analysis of Distance and Time Requirements

At this stage, the aim is to find out the estimated time span needed to reach a safe place or Potential TES (Temporary Evacuation Shelter) before the tsunami arrives or ETA (Estimated Time Arrival) evacuation. It is generally assumed that a tsunami could arrive within approximately 30 minutes after the earthquake; however, this estimation may vary depending on the tsunami source characteristics. The TES potential is as follows:

Table 1. Potential TES in Padang Barat

No	Building Name
1	Escape Building Kantor Gubernur Sumbar
2	Pasar Raya Blok III
3	STBA Prayoga
4	SD Agnes
5	SMP Negeri 2 Padang
6	Hotel Truntum
7	Pasar Raya Blok I
8	Pasar Raya Blok II
9	Pasar Raya Blok IV
10	SD Negeri 23 dan 24 Ujung Gurun

The potential shelter building also functions as a socio-economic building used in social activities, not only as a tsunami wave barrier [11]. The data analysis began with the determination of the evacuation starting point. The selected coordinate (0°56'35"S 100°21'09"E) corresponds to a public location at the center of West Padang sub-district, characterized by high population density and direct access to primary evacuation routes, making it a representative reference point for evacuation modeling**.** Then, calculate the distance from the starting point to the potential shelter location, and find the actual evacuation time (Rst), according to [21], Rst using Eq.1.

$$\boldsymbol{RsT = ETA - ToNW - RT} \quad (1)$$

Which,

$$\boldsymbol{ToNW = IDT + INT} \quad (2)$$

Human response capability depends on the estimated time of arrival (ETA) of a tsunami, the time when technical or natural warning signs, Eq. 2, ToNW, determined by Institutional Decision Time IDT and Notification Time INT, can be accepted by the residents, and the reaction time. (RT).

After obtaining the actual tsunami evacuation time, the evacuation time needed (ETA) is then calculated. To calculate the ETA, the following calculation is used Eq. 3.

$$\boldsymbol{ETA} = \boldsymbol{L}\frac{\boldsymbol{t}}{\boldsymbol{V}} \quad (3)$$

After obtaining the length of the evacuation route L multiplied by the time multiplying factor t divided by the speed of the evacuation person V, the time multiplying factor is 0.751m/sec. To get the value of people's speed in the evacuation process, it will be calculated by simulating from the starting point by tracing the nearest evacuation route to the available shelter. This study adopts a uniform walking speed of 2.41 m/s and a time multiplier of 0.751 based on established references [15- 18], which are commonly used in tsunami evacuation modeling. These values are applied to provide a standardized baseline for estimating evacuation time across all routes. While variations in individual mobility, terrain conditions, and behavioral factors such as congestion or panic may influence real-life evacuation dynamics, the selected parameters offer a consistent and practical framework for comparative analysis in the context of the West Padang sub-district.

Evacuation route mapping was conducted using ArcGIS 10.8, utilizing underlying spatial data and base maps to reflect local geographic features. Given the relatively flat topography of the study area, elevation differences are considered to have minimal influence on walking speed and route accessibility. Additionally, potential shelters were selected based on structural soundness, capacity, and proximity to residential areas. Their coordinates and evacuation routes were digitized in ArcGIS 10.8 by simulating from the designated starting point to the nearest shelter, in order to produce a realistic and contextually relevant evacuation planning model.

3.2 Analysis of Community Understanding

Mitigation begins with local communities assessing the risks they face due to recurring issues and creating plans to develop solutions to these problems, as well as reducing the vulnerability of residents and their properties to risks. This questionnaire is designed to measure the level of public understanding about tsunamis in tsunami-prone areas, specifically in the West Padang sub-district. The educational background of respondents was recorded to examine the influence of education level on the implementation of disaster mitigation practices. This information supports the analysis of the gap between knowledge and practical implementation identified in the study findings. The survey involved 100 respondents. Although demographic stratification—such as age, occupation, and proximity to the coast—was not applied, these variables are acknowledged as significant and are recommended for consideration in future studies to obtain a more comprehensive understanding of variations in community preparedness.

Researchers used a type of closed questionnaire, which means that the distributed questionnaire already provided answers, allowing respondents to simply choose and check. The questionnaire designed for this research was created using the Guttman Scale. The Guttman Scale measures variables with more definitive answer types, namely "Yes and No," "True and False." This study employs the response technique of "Yes" or "No" and "Ever" or "Never," with "Yes" and "Ever" scored as one and "No" and "Never" scored as 0. The criteria for the questionnaire answers are 0-50% low and 50-100% good. The research data collection questionnaire, prepared by the researcher based on previous questionnaires, has its instrument framework outlined as shown in the table below:

Table 2. Research Instrument

Variable	Indicator
Factors influencing disaster mitigation	Experience Knowledge Implementation

After obtaining the scores from each question, the next step is to calculate the high and low values present. The respondents' answers on the questionnaire can be grouped into an interval scale. The following is a rating scale in percentages to interpret the value of questionnaire questions:

Table 3. Interval Respondent's Answer

Percentage Interval	Category
51-100	Good
0-50	Not enough

3.2.1 Validity and Reliability Test

The validity and reliability tests need to be conducted on the measurement tools that will be used in the research. The results of the validity and reliability testing of the indicators in this study were all obtained using the SPSS Statistics 22.0 software. The reliability test produced a Cronbach’s Alpha value of 0.905, indicating excellent internal consistency. This confirms that the questionnaire is a reliable instrument for assessing community understanding of disaster mitigation.

4. RESULT

4.1 Parameter Analysis of Distance and Time Requirements

Based on the research conducted previously, it is known that there are 10 potential shelters in the Padang Barat sub-district. The distribution of potential shelters in the Padang Barat Sub-district is shown in Figure 1. The shelter locations were mapped using ArcGIS 10.8, with data sourced from local building surveys, tsunami risk zoning maps, and accessibility analysis. Each shelter was selected based on factors such as structural height, accessibility, and public function. However, this study did not include a structural strength analysis or an evaluation of the vertical load-bearing capacity of the ten identified potential shelters under seismic conditions. The focus of the research was on assessing the feasibility of evacuation in terms of time and distance under ideal conditions, which aligns with the primary objective of mapping potential accessibility for the affected communities. After identifying the distribution of potential shelters, the next step is to determine the evacuation routes and calculate the distance from the evacuation starting point to the nearest shelter.

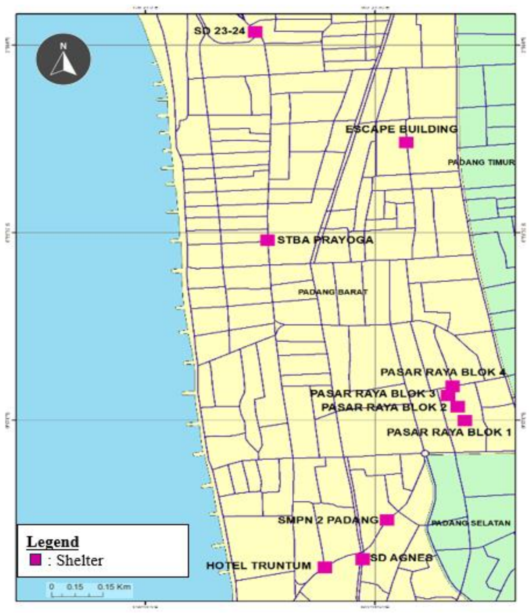

Fig. 1. Potential Shelter Location Map

To determine the distance from the starting point to the potential shelter, measurements will be taken from the starting point to the available potential shelter. After measuring from the starting point to the potential shelter, the distance from the starting point to each potential shelter is obtained as follows:

Table 4. Potential Shelter Distance

No	Building Name	Distance (m)
1	Escape Building Kantor Gubernur Sumbar	1420
2	Pasar Raya Blok III	1580
3	STBA Prayoga	480
4	SD Agnes	1950
5	SMP Negeri 2 Padang	1980
6	Hotel Truntum	1930
7	Pasar Raya Blok I	1710
8	Pasar Raya Blok II	1650
9	Pasar Raya Blok IV	1670
10	SD Negeri 23 dan 24 Ujung Gurun	1370

The closest potential shelter from the starting point is the STBA Prayoga shelter, while the farthest potential shelter from the starting point is the SMPN 2 Padang shelter.

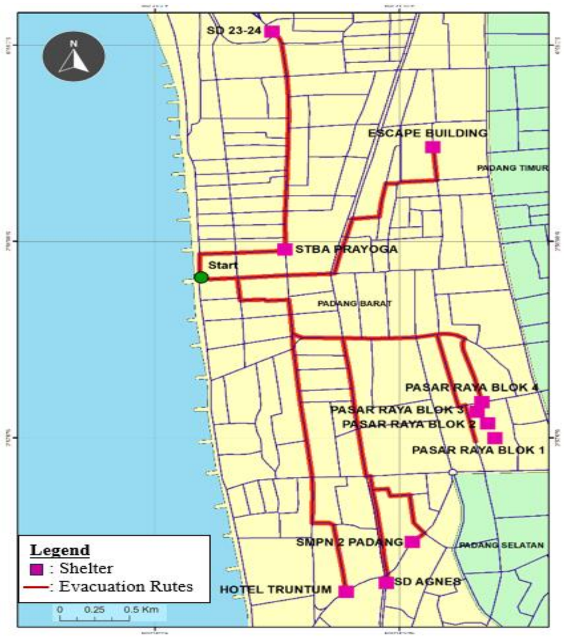

Fig. 2. Evacuation Routes to Potential Shelters

Routes were generated using ArcGIS Network Analyst, considering existing road networks and realistic travel paths to reflect actual evacuation scenarios. After obtaining a route for the evacuation process, the next step is to calculate the actual evacuation time in the West Padang sub-district. The calculation of actual evacuation time indeed uses Eq. 1 and Eq. 2.

$$\boldsymbol{RsT} = \boldsymbol{ETA} - \boldsymbol{ToNW} - \boldsymbol{RT} \quad (1)$$

Which,

$$\boldsymbol{ToNW} = \boldsymbol{IDT} + \boldsymbol{INT} \quad (2)$$

ETA = 1800 seconds Padang City [22]
IDT = 180 seconds Earthquake data processing by BMKG [23]
INT = 300 seconds Dissemination of tsunami information by BMKG [23]
RT = 300 seconds [24]
So that,

$$\boldsymbol{RsT} = \boldsymbol{ETA} - \boldsymbol{ToNW} - \boldsymbol{RT}$$
$$\boldsymbol{RsT} = \mathbf{1800}\,\boldsymbol{s} - (\mathbf{180}\,\boldsymbol{s} + \mathbf{300}\,\boldsymbol{s}) - \mathbf{300}\,\boldsymbol{s}$$
$$\boldsymbol{RsT} = \text{RST}$$

minutes actual time for the evacuation process

Within the actual evacuation time of 17 minutes/1020 seconds, the refugees had to reach an area safe from the danger of the tsunami. In areas with critical evacuation times, such as at the research location, emergency evacuation places are needed in the form of potential shelter buildings. However, the

17 minutes/1020 seconds evacuation time identified in this study is based on ideal conditions and does not take into account real-world factors such as physical obstacles along the evacuation routes, congestion due to crowds, or delays caused by panic.

After obtaining the actual evacuation time, the next step is to calculate the estimated evacuation time to the potential shelter building. Previously, the distance from the starting point to the potential shelter had been calculated, and the data from that distance is processed using Eq.3.

$$\boldsymbol{ETA} = \boldsymbol{L}\frac{\boldsymbol{t}}{\boldsymbol{V}} \tag{3}$$

The analysis of distance and time requirements is carried out by carrying out simulations from the shoreline to existing potential shelters, in order to obtain calculations of the distance from the shoreline to the shelter (L), running speed (V), time multiplier factor (t) to obtain evacuation arrival time (ETA) results.) at each potential shelter. The results of the data obtained are as follows:

Table 5. ETA to Potential Shelter

No	Potential Shelter	Distance (L) (meter)	speed (V)	time multiplier factor (t)	ETA
1	Escape Building Kantor Gubernur Sumbar	1420	2,41 m/s	0,751	00.07.22
2	Pasar Raya Blok III	1580	2,41 m/s	0,751	00.08.12
3	STBA Prayoga	480	2,41 m/s	0,751	00.02.30
4	SD Agnes	1950	2,41 m/s	0,751	00.10.08
5	SMP Negeri 2 Padang	1980	2,41 m/s	0,751	00.10.17
6	Hotel Truntum	1930	2,41 m/s	0,751	00.10.01
7	Pasar Raya Blok I	1710	2,41 m/s	0,751	00.08.53
8	Pasar Raya Blok II	1650	2,41 m/s	0,751	00.08.34
9	Pasar Raya Blok IV	1670	2,41 m/s	0,751	00.08.40
10	SD Negeri 23 dan 24 Ujung Gurun	1370	2,41 m/s	0,751	00.07.07

The data processing to determine the tsunami arrival time is conducted by dividing the length of the evacuation route (L), from the shoreline to the shelter, by a person's walking speed (V), and then multiplying by a time factor (t). The time factor value for evacuation is evaluated using the values provided in the table below, adjusted to the conditions during the tsunami prediction, with a walking speed of 0.751 m/s.

Based on the analysis of the calculated distance and time requirements, the fastest estimated time of arrival (ETA) is at the STBA Prayoga potential shelter, with a travel time of 2 minutes 30 seconds from the shoreline. Meanwhile, the longest ETA is at the SMPN 2 Padang potential shelter, with a travel time of 10 minutes 17 seconds from the starting point.

4.2 Analysis of Community Understanding

4.2.1 Validity Test

The validation test is a measure used to determine the level of validity of an instrument. An instrument is considered valid if it can accurately capture data from the variables being studied. The validation test of the research instrument was conducted using the SPSS program. Decisions regarding whether a question item is valid or invalid were made by comparing the r-count value with the r-table value. Based on the results of the instrument trial with 30 respondents (n = 30), the r-table value was 0.361; thus, a question item was considered valid if the r-count was greater than the r-table value [26]. The results of the validity testing showed that 7 out of 40 question items were invalid. Consequently, 33 question items were retained to be used as the research instrument.

4.2.2 Test Reliability

Reliability testing determines the level of stability of the measuring instrument. This reliability test was carried out after testing the validity of the questionnaire used. An instrument is considered reliable or trustworthy if the response to the statement is consistent or stable over time. The reliability of research instruments shows that an instrument is reliable enough to be used as a data collection tool. The correlation coefficient is consulted with the reliability index as follows:

Table 6. Interpretation of the value of r.

Coefficient Interval	Interpretation
Between 0,800 to 1,00	Very high
Between 0,600 to 0,800	Height
Between 0,400 to 0,600	High Enough
Between 0,200 to 0,400	Low
Between 0,000 to 0,200	Very low

From the results of the calculated r test, the Cronbach alpha value = 0.905 was obtained, which is included in the high interpretation, so it was concluded that all the statement items used in the questionnaire were reliable, which means that there were similarities in the data at different times and the resulting data was accurate.

4.2.3 Results of the Questionnaire Distribution in Padang Barat sub-district

The results of the questionnaire distribution were obtained based on an analysis of the level of experience, knowledge and implementation of mitigation for the community living in West Padang sub-district against the earthquake and tsunami disaster. The assessment indicators are as follows:

Table 7. Results of the Questionnaire Distribution in Padang Barat sub-district

Indicator	Score Result	Score Total	Percentage
Experience	907	1500	60,4%
Knowledge	834	1000	83,4%
Implementation	476	800	59,5%

The results of a questionnaire distributed to 100 respondents in West Padang District, Padang City, indicate that the community's level of understanding regarding disaster evacuation is generally adequate. Based on the experience indicator, a respondent achievement rate of 60.4% reflects a moderate level of prior involvement in tsunami-related activities, such as evacuation drills or real events. This is consistent with the historical disaster records in Padang, where major earthquakes and tsunamis occurred in 2004 and 2009. For the knowledge indicator, respondents achieved a score of 83.4%, indicating a good understanding of general evacuation information. However, the implementation indicator yielded a lower achievement rate of 59.5%, suggesting a gap between knowledge and practical action. One potential contributing factor to this gap is educational background, with the majority of respondents (approximately 68%) having at least a senior high school education, while the remainder had only completed primary or junior high school.

5. CONCLUSION

This study integrates geospatial route modeling with community-based survey data to evaluate tsunami evacuation preparedness in West Padang sub-district. Spatiotemporal analysis demonstrates that all ten identified shelters fall within the operative 17-minute evacuation window, with estimated times of arrival ranging from 2 min 30 s at STBA Prayoga to 10 min 17 s at SMPN 2 Padang. Survey responses (n = 100) yielded mean scores of 60.4 % for evacuation experience, 83.4 % for knowledge, and 59.5 % for implementation, indicating high awareness but underscoring operational limitations in practical execution.

A uniform walking speed of 2.41 m/s and a time multiplier of 0.751 were applied to straight-line routes digitized in ArcGIS 10.8, establishing a standardized baseline for ETA modeling. Future work should refine these parameters via demographic-specific speed profiles, incorporate road-network and optimal-path analyses, and validate results through dynamic simulations or field-based evacuation drills to enhance model realism and predictive accuracy in high-risk coastal environments. Future research will aim to integrate real-time tsunami modeling and dynamic evacuation simulations to enhance the predictive accuracy and practical applicability of the findings for disaster risk reduction policy.

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