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Determination of closest facility tsunami evacuation building using GIS Heuristic Method: A Case Study of Meuraxa District, Banda Aceh City

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ABSTRAK

Indonesia, characterized by its susceptibility to natural calamities such as seismic activities, tsunamis, inundations, and volcanic eruptions, experienced a significant event on December 26, 2004, when a seismic event measuring 9.1 in magnitude occurred off the northern Sumatran coast, precipitating a tsunami with particularly severe repercussions in the Aceh province. The absence of preemptive measures exacerbated the catastrophe, leading to a substantial loss of lives. Subsequent to this incident, the implementation of Tsunami Evacuation Buildings (TEB) has been underway as a preventive measure against potential tsunami disasters. The construction process involves utilizing Geographic Information System (GIS) technology for mapping during evacuations. The escalating population has rendered the existing TEB facilities insufficient for evacuation purposes, necessitating the construction of additional TEB structures. The determination of TEB locations involves a location-allocation analysis, with subsequent assessment of the nearest routes conducted through closest facility analysis. Research findings indicate that the incorporation of three new TEBs has proven effective in facilitating timely evacuation during tsunamis, accommodating a population of 6,528 within a maximum duration of 22 minutes, with a maximum capacity of 11,808. However, it is noteworthy that the efficacy of these facilities is contingent upon factors such as the condition of the building's ground floor in the event of a tsunami-induced flooding, which may influence the overall capacity.

Keywords: TEB; GIS; location-allocation; closest facility

1. INTRODUCTION

Indonesia is a nation frequently afflicted by natural disasters, with specific regions facing heightened susceptibility, notably to earthquakes, tsunamis, floods, and volcanic eruptions. As exemplified by the seismic and tsunami events in Aceh in 2004, this region is identified as earthquake-prone, with a concomitant potential for ensuing tsunamis threatening the Aceh coastal zone [1]. Subsequent seismic activity subsequent to the December 26, 2004 earthquake significantly impacted the Aceh coastal area, resulting in land subsidence and an increased ingress of seawater, thereby inundating refugee areas. The substantial population residing along the Aceh coast is more predisposed to heightened tsunami-related risks, with projections indicating a greater potential for fatalities compared to inland areas [2].

Tsunamis possess the capacity to swiftly propagate, resulting in substantial devastation within regions prone to such events. The limited timeframe available for issuing prompt public warnings and facilitating evacuations is further constrained by an inadequate infrastructure and the absence of systems for effectively disseminating early warnings to the community [3]. The deficiency in tsunami monitoring and early warning mechanisms contributes to community unpreparedness, leaving insufficient time for residents to reach designated evacuation sites, consequently culminating in a high incidence of fatalities and significant damage. The ramifications of earthquakes and tsunamis extend across both physical and non-physical domains, encompassing tangible impacts such as structural damage to residences, offices, and economic centers, as well as intangible consequences like health and psychological challenges, and disruptions to educational pursuits [4].

In 2004, Aceh experienced a substantial earthquake and tsunami calamity, prompting a sense of panic within the community during evacuation, primarily attributable to the absence of adequate evacuation facilities. The dearth of secure shelter options compelled a majority of the populace to resort to evacuating towards elevated areas using motor vehicles, thereby precipitating traffic congestion on certain routes and impeding the efficiency of the evacuation procedure. Furthermore, the infrastructure in Banda Aceh City suffered severe impairment, with numerous bridges sustaining damage, city roads being obstructed by debris, and widespread fissuring of road surfaces [5][6].

Insufficient proximate evacuation infrastructure emerged as a contributing factor to the elevated casualty rates observed in the 2004 Aceh earthquake and tsunami disaster. Furthermore, numerous structures designated as evacuation sites fell short of meeting essential safety criteria, including inadequacies such as a lack of sufficient exits or failure to comply with disaster evacuation safety standards [2].

The 2004 tsunami incident in the Aceh province stands as a instructive precedent for diminishing both human casualties and property damage in prospective events. Disaster mitigation, comprising proactive measures, is pivotal in mitigating the repercussions of disasters. This involves a comprehensive examination of both natural and anthropogenic settings, assessing risks and vulnerabilities, and comprehending human behavior in the context of disaster scenarios. Such endeavors are instrumental in curtailing losses during disaster events and facilitating the recovery process post-disaster [7]. From the background explanation, this research aims to provide specific guidance and recommendations for reliable tsunami mitigation planning, with a focus on optimizing evacuation facilities, enhancing capacity, and prevention to improve community safety in facing the potential tsunami disaster.

2. LITERATURE REVIEW

The occurrence of a natural disaster 18 years ago has prompted global reconsideration of the spatial organization of Aceh Province, an area susceptible to earthquakes and tsunamis [1]. The government has persistently undertaken initiatives in response to seismic and tsunami events, focusing on the establishment of temporary evacuation places (TES), specifically tsunami evacuation buildings (TEB). Strategic placement of these evacuation structures near population centers, accessible via roadways and transportation networks, is emphasized. In situations where evacuation is impractical, these buildings serve as viable temporary shelters, providing an effective means for individuals to protect themselves from natural disasters such as earthquakes and tsunamis [3].

Tsunami evacuation structures situated along coastal regions play a pivotal role as temporary refuges for inhabitants present in those areas during a tsunami event. These edifices necessitate compliance with rigorous safety standards and must undergo evaluation prior to their designation as evacuation sites. The existence of well-equipped tsunami evacuation buildings along the coast enables expeditious shelter for citizens, mitigating the peril of tsunamis and thereby diminishing the incidence of fatalities and property damage. Moreover, these evacuation facilities can serve as provisional shelters for individuals who have incurred displacement and property loss resulting from a tsunami. The seismic activity induced by movements in tectonic plates is denoted as tectonic earthquakes [8].

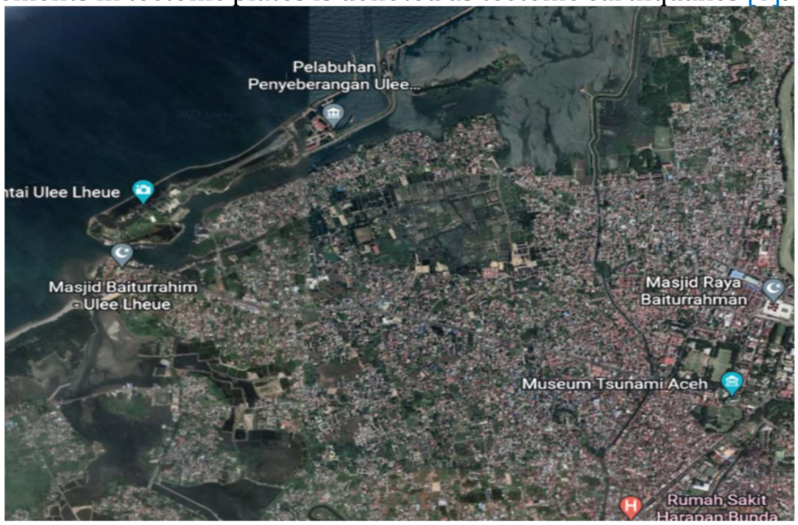

Figure 1. Map of Banda Aceh City Area

Figure 1 depicts the map of the Banda Aceh region in the Aceh Province, Indonesia, which is a strategically located area with a complex geographical condition. Indonesia, as a country situated at the intersection of three major global tectonic plates—namely the Eurasian plate, the Pacific plate, and the Indo-Australian plate—is also involved in interactions with a microplate, namely the Philippine plate. The tectonic configuration involving these plates makes Indonesia susceptible to seismic events, particularly earthquakes and tsunamis. The seismic event that marked its history in Aceh in 2004 was identified as a megathrust earthquake, occurring in the early subduction zone. The Aceh Province is surrounded by two active fault segments, namely the Aceh Segment Fault and the Seulimum Segment Fault, both of which are estimated to be capable of causing significant seismic activity and have the potential to trigger tsunamis [9][10].

The 2004 Aceh tsunami resulted from a seismic event of 9.1 magnitude originating on the floor of the Indian Ocean, approximately 150 km off the coast of Aceh, Indonesia. The ensuing tsunami waves, generated by this earthquake, exhibited substantial magnitude and devastation, attaining heights of up to 30 meters along the Aceh coastline and propagating across the entire Indian Ocean region. Consequently, the tsunami wrought extensive damage and incurred a significant loss of life in Aceh and its vicinity, as well as in neighboring countries [11]. The impact of tsunami waves is capable of extending tens of kilometers inland from the shore. The detrimental consequences, both in terms of damage and loss of life, arise from the forceful impact of water and materials transported by the tsunami currents [12][13].

Following the standard operating procedures (SOPs) established by the Meteorology, Climatology, and Geophysics Agency, in the event of an earthquake and tsunami disaster, a series of sequential measures are undertaken. Detection of the earthquake is prioritized within the initial 3 minutes, followed by a potential disaster analysis in the fourth minute. Subsequently, earthquake warnings and relevant information are issued in the fifth minute, with broader dissemination of earthquake details and tsunami warnings completed within 10 minutes. The evacuation phase spans from 10 to 20 minutes, aligning with the anticipated arrival of the tsunami in less than 40 minutes, and the confirmation of tsunami warning cancellation occurs beyond the 40-minute mark [14]. It is imperative to initiate evacuation promptly upon receiving the warning, given the exceedingly constrained timeframe available for evacuation.

The demographic data for the city of Banda Aceh in 2019, as projected, indicates a population of 270,321 individuals, comprising 138,993 males and 131,328 females [15]. This investigation employs geographic information system (GIS), or Sistem Informasi Geografis (SIG), for the processing and storage of data as well as geographic information. SIG is adept at connecting diverse data points on Earth, amalgamating them, conducting analysis, and ultimately generating maps based on the results. The data utilized and processed in SIG pertains to spatial data, characterized by a geographic orientation and a specific coordinate system as its reference base. Consequently, SIG can address inquiries related to location, conditions, trends, patterns, and modeling through a particular category of SIG analysis, namely network analysis [16].

Geographical information system (GIS) employs network analysis to scrutinize geographical networks and address diverse issues, including identifying the most expeditious or shortest route, locating the nearest facilities, and delineating service areas [17]. This study aims to ascertain the optimal placement of tsunami evacuation buildings (TEB) concerning the spatial distribution of residential structures within the Meruraxa sub-district of Banda Aceh City. The objective is to facilitate swift accessibility for the community in Meuraxa sub-district to the TEB, thereby minimizing potential casualties in the event of an earthquake and tsunami disaster. Determination of the TEB location involves aligning existing residential points and considering the current population of Banda Aceh City, utilizing the ArcGIS software.

3. METHOD

In the present study, a qualitative methodology was employed. The qualitative analytical approach involved the acquisition of data pertaining to the geographical placement and structural capacity of individual edifices. Examination of road accessibility to buildings in times of disaster, stakeholder interviews, and subsequent data analysis utilizing the ArcGIS application constituted integral components of the investigative process.

A. Research variable

In the event of a tsunami disaster, the variable adheres to the specifications delineated by the BSN (National Standardization Agency) with respect to SNI 7766 (2012) concerning tsunami evacuation pathways. These guidelines are systematically presented in Table 1.

Table 1. Research variable

Data Source	Interview
Interview with BPBD	- Evacuation Point - Building area - Number of floors of the building - Building capacity - Distance from the coastline - Location of the road - Safe zone from tsunami hazards
Adjustment with GIS (Geographic Information System) data	- Evacuation Route - Travel time - Standard road width - Road network (road condition)

B. Data collection method

The data acquisition approach employed in this study encompasses two types of data: primary data, serving as the principal dataset, and secondary data, utilized as supplementary information.

i.) Primary data

Table 2 the acquisition of primary data involves the execution of observations and interviews with academic professionals. Interviews are specifically carried out with representatives from local governments, particularly the BPDP, to gather contemporary issues and pertinent data for the research. Subsequently, the interview findings will be processed to serve as a reference for decision-making in the event of a disaster. Observational data is aligned by cross-referencing information obtained with data accessible on the government's Geographic Information System (GIS) website.

Table 2. Primary data

Data Source	Interview	Source
Evacuation Point	Building area Number of floors of the building Building capacity Distance from the coastline Location of the road Safe zone from tsunami hazards	Dito & Pamungkas (2015)
Evacuation Route	Travel time Standard road width Road network (road condition)	SNI 7766 (2012) Ashar, Amaratungam & Heigh

i.) Secondary data

Table 3 secondary data is acquired through the retrieval of information from the official government website or relevant stakeholders involved in the research. This supplementary data serves as an additional information source, contributing to the comprehensive data processing undertaken in the research.

Table 3. Secondary data

Data Source	Type of Data
TDMRC (Tsunami and Disaster Mitigation Research Center)	Location of emergency shelter points Location of TEB (Tsunami Evacuation Buildings) Latest TEB development plan
BAPPEDA Banda	*Shape file of Banda Aceh City* Map of road network
BPS Banda Aceh	Population data of Banda Aceh in 2020 Tsunami victim data in 2004
BPBD Banda Aceh	Strategy for tsunami evacuation and mitigation

C. Analysis method

The analytical methodology employed in this study is categorized into three distinct components: analysis of time allocation for tsunami evacuation, examination of the nearest facilities, and location allocation analysis.

i.) Tsunami evacuation time allocation analysis

Preceding the onset of a tsunami disaster, preliminary seismic activity and other natural warnings will manifest. Consequently, there exists a need for identification procedures to compute the time allocation for evacuation. The evaluation of evacuation time involves the utilization of the following formula as an indicator:

TTime = ETA – ToNW – RT (1)
ToNW = IDT + INT (2)
Explanation:
TTime = Time required for evacuation
ETA = Estimation of tsunami arrival (40 minutes)
ToNW = Technical warning (8 minutes)
RT = Resident's reaction time (10 minutes)
IDT = Decision-making time of the agency (5 minutes)
INT = Government agency warning time (3 minutes))

The aforementioned formula is employed to determine Time Travel. Subsequently, this formula will be input into the Geographic Information System (GIS) to ascertain the duration it takes for residents to reach the closest tsunami evacuation building (TEB) from their residences.

ii.) Closest facilities analysis

Spatial analysis for the closest facilities is conducted using network analysis tools within the ArcGIS application. This examination focuses on determining the optimal and efficient locations of residences in the Meuraxa District of Banda Aceh City, ensuring effective access to tsunami evacuation buildings (TEBs). The evaluation takes into account factors such as the population density around each building and the allocated time required for reaching the designated structures. Figure 2 below is a related flow diagram for the nearest facilities.

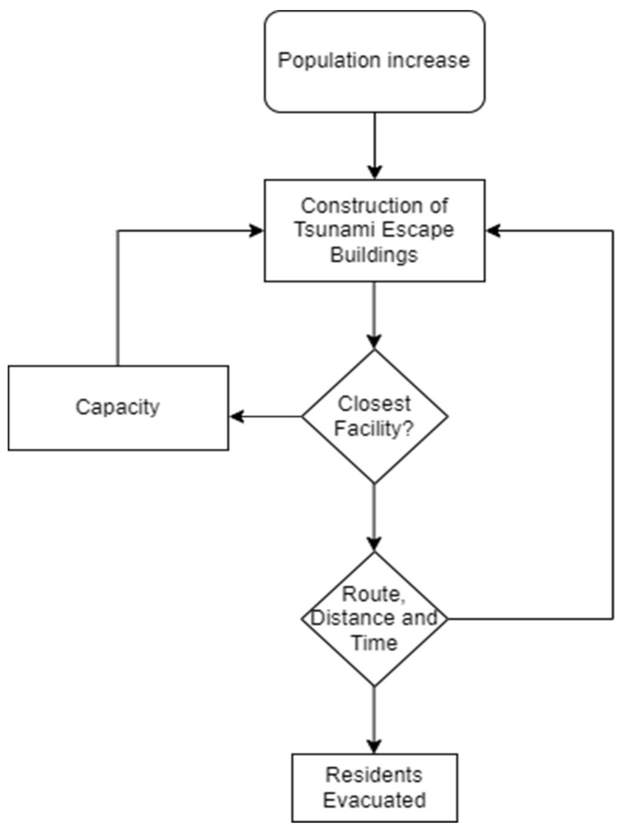

Figure 2. Flowchart of closest facilities

4. RESULT AND DISCUSSION

4.1 Location-allocation analysis

In the context of location-allocation analysis, a survey interview was undertaken with the regional meteorology, climatology, and geophysics agency (BMKG) to ascertain the geographical placement of extant temporary evacuation buildings (TEBs). Concurrently, calculations were executed to assess the evacuation capacity of these TEBs during disaster scenarios, as detailed in **Table 4**. Following the acquisition of TEB point data, spatial mapping was performed using the ArcGIS application, wherein longitude and latitude coordinates corresponding to the building positions were inputted. The resultant location points are visually represented on the map.

Table 4. Location and capacity table

No	Source	Long	Lat	Capacity (People)
1	TEB1	95.293500	5.559399	1829
2	TEB2	95.285770	5.553662	2029
3	TEB3	95.292454	5.554732	480
4	TEB4	95.303141	5.563772	1470
		Total		**5808**

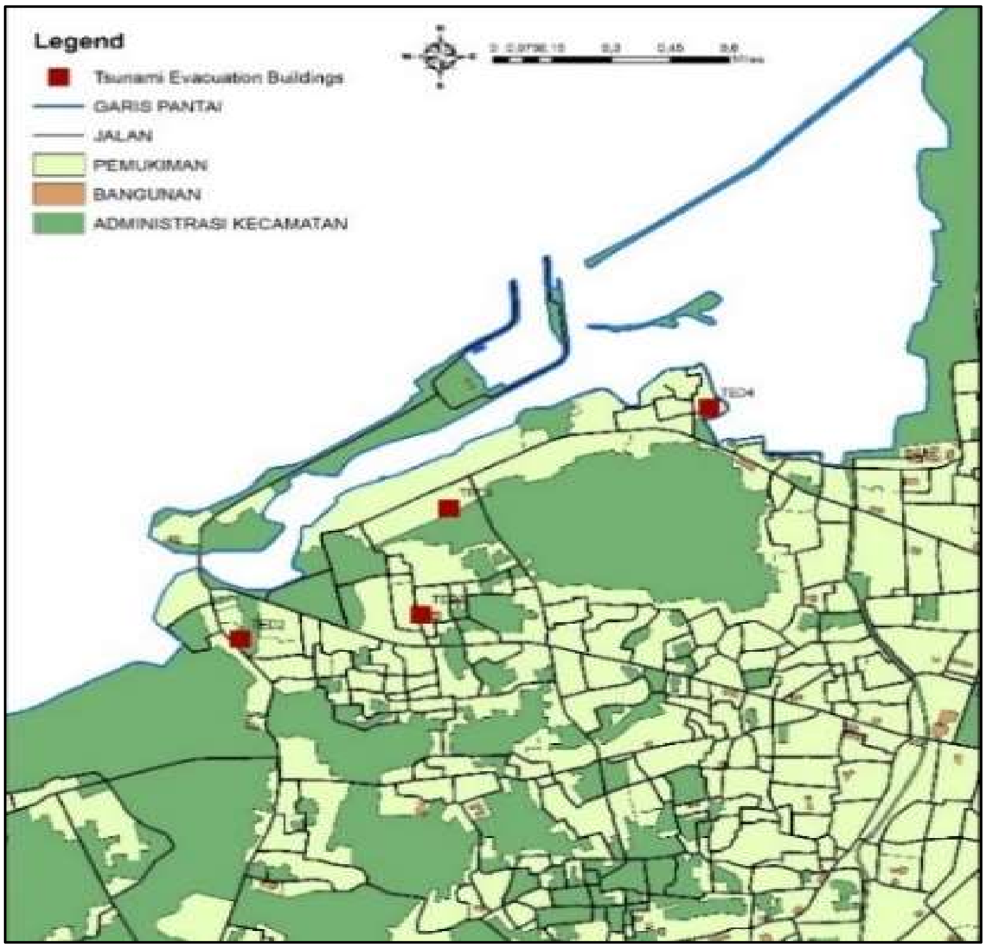

Figure 3. TEB Location

In the illustration found in **Figure 3**, it is explained that within the framework of the location determination analysis for the initial four temporary evacuation buildings (TEBs), specifically marked in red in the legend, and located in the coastal area vulnerable to tsunami impact, it is observed that the average distance of these structures from the shoreline is approximately 1000 meters. This occurrence can be linked to the high population density in that area, making it susceptible to significant vulnerability and severe impact during tsunami events. Following the completion of the location determination analysis, specific areas were identified where the TEB capacities exceeded the established limits, as detailed in the **Table 5** presented below.

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Table 5. TEB capacity and coverage table

Building	Building capacity (people)	Floor of building (people)	Reachable Village
TEB1	1218	611	Deah Glumpang
TEB2	1332	697	Ulhe lheu
TEB3	320	160	Lambhung, Blang Oi, Cot Lamkeuweh
TEB4	1165	305	Alue Deah Tengoh
Total	**4035**	**1773**	

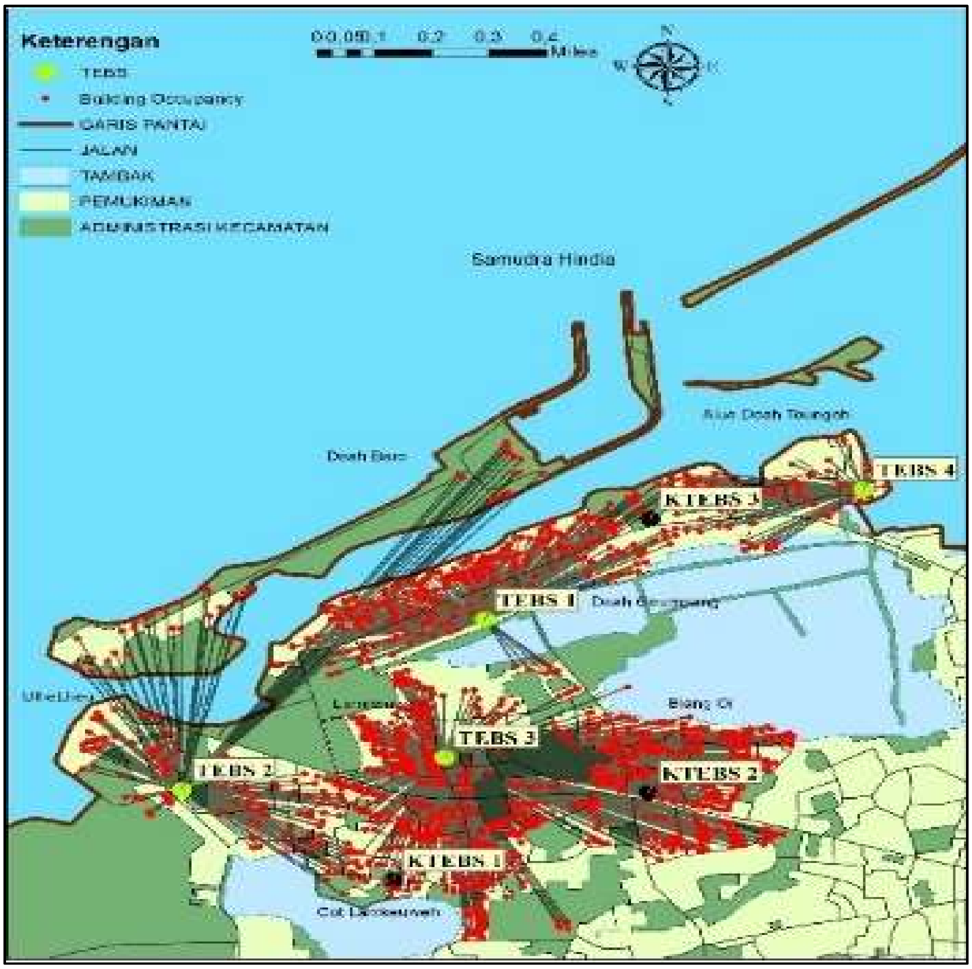

Figure 4. Existing TEB area reach

The identification of residential building locations connected to existing temporary evacuation buildings (TEBs) indicates an extensive spatial coverage in the Lambhung, Blang Oi, and Cot Lamkeuweh areas, resulting in inefficiency, as illustrated in **Figure 4** above. The urgent evacuation count for these areas reaches 6,528 individuals, a figure that raises safety concerns considering the corresponding building capacity is limited to accommodating only 5,808 people. The Table 6 presents the movement and access times to densely populated buildings, as detailed in reference [15]

Table 6. Table of access time for existing TEBs

Building	Access Time (minutes)	Number Evacuated (people)
TEB 1	0 – 5	676

Building	Access Time (minutes)	Number Evacuated (people)
	5 – 17	512
	17 – 22	74
TEB 2	0 – 5	31
	5 – 17	903
	17 – 22	643
TEB 3	0 – 5	358
	5 – 17	843
	17 – 22	184
TEB 4	0 – 5	184
	5 – 17	966
	17 – 22	574
Number of evacuated population		**6528**
Maximum number of TEBs		**5808**

The presented table constitutes a mitigation strategy aligned with the indonesian national standard (SNI). It outlines the estimated evacuation times from the building occupancy areas to the temporary evacuation buildings (TEBs), which are stipulated as 5, 17, and 22 minutes for immediate evacuation to the nearest TEB. The proximity of the TEB is deliberated, taking into account factors such as panic and travel time during the evacuation, with a specified maximum limit of 22 minutes following an official government agency announcement for evacuation. Beyond this timeframe, it is anticipated that the tsunami would have reached the coastal region. Failure to reach the TEB within the designated 22-minute travel time in the nearest coastal area may result in a loss of lives.

Observationally, there remains a cohort of 720 residents who currently lack coverage under the existing tsunami prevention mitigation measures. This resident count does not account for the potential impact of water inundation on the ground floor of temporary evacuation buildings (TEBs) caused by tsunami currents. Additionally, the demographic data fails to incorporate calculations pertaining to population growth based on the most recent survey conducted in 2022. Consequently, there arises a necessity to construct new TEBs characterized by medium- to long-term designs, ensuring comprehensive coverage for all residents susceptible to the impacts of natural disasters, including earthquakes and tsunamis.

In the context of temporary evacuation building (TEB) allocation, TEB 3 situated in Lambhung Village exhibits a maximum capacity of approximately 1829 individuals. Notably, this structure also serves two other villages—Blang Oi and Cot Lamkeuweh—highlighting its broader coverage. In contrast, TEB 2 boasts a substantial total capacity of 2029 people, surpassing that of TEB 3. TEB 2 effectively addresses the population distribution in Ulhee Lheue, Deah Glumpang, and a portion of Cot Lamkeuweh villages. However, TEB 1, designated for the Deah Glumpang area with a capacity of 480 people, faces overload issues due to the population of Deah Glumpang exceeding the building's capacity, with a population spread of 1385 people. As for TEB 4, covering the Alue Deah Teungoh area, it accommodates 1470 people, leaving 70 individuals without coverage.

4.2 Analysis of the proposed closest facility TEB

In the preceding analysis involving four temporary evacuation buildings (TEBs), certain regions were identified as inadequately covered. Consequently, there is a imperative need to establish additional TEBs in close proximity to address populations currently beyond the existing reach and capacity. In the scope of this study, a proposal is put forth to construct three new TEB candidates strategically positioned to extend coverage to areas currently lacking sufficient protection.

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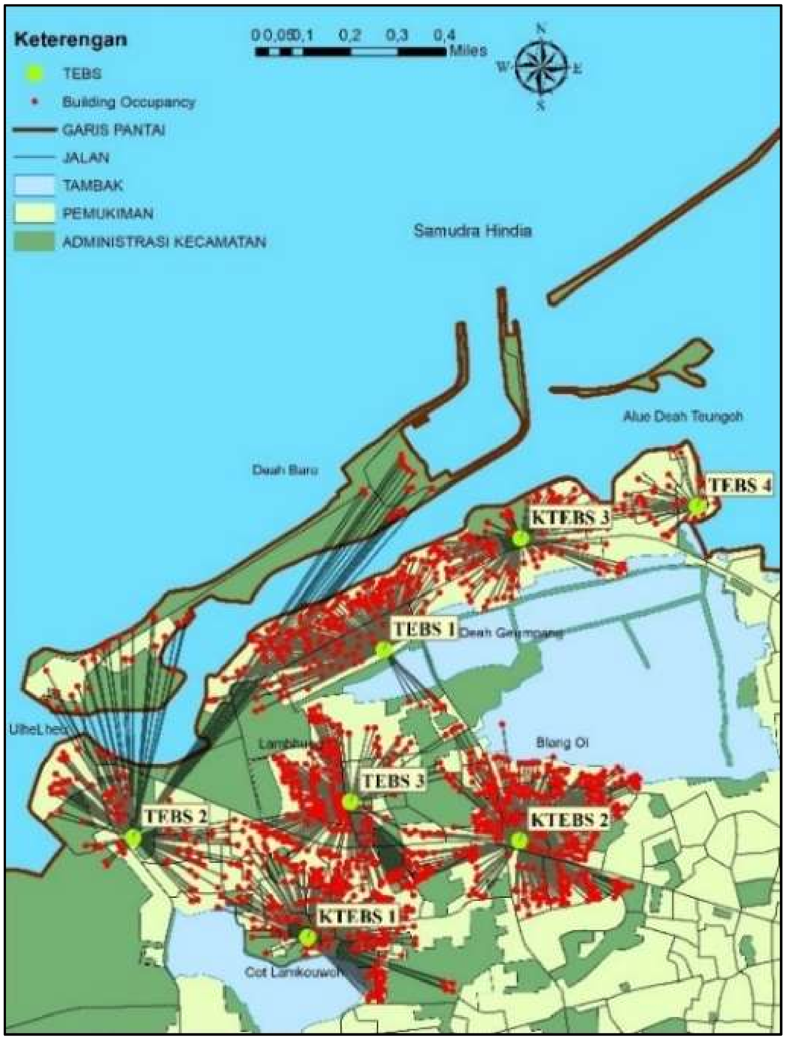

Figure 5. Proposed closest facility TEB

In the illustration in Figure 5 above, the distribution of residential areas is explained alongside the placement of prospective Temporary Evacuation Buildings (TEBs). Previous analysis indicates that the positioning of KTEB 1 was entirely covered by TEB 2, a configuration considered inefficient due to the high population density in the area, increasing the risk of exceeding the TEB capacity. By incorporating KTEB 1 into this location, comprehensive coverage of the community with adequate capacity is ensured. Additionally, KTEB 2 now includes the population residing in the Blang Oi area, previously served by TEB 3. Furthermore, KTEB 3 addresses the needs of the population in parts of Deah Glumpang and Alue Deah Tengoh Villages, areas that were previously outside the coverage of TEB 1 and TEB 4 **Table 7**. The proposed integration of temporary evacuation buildings (TEBs) has a significant impact on both access time to the TEB and the accommodated capacity. These modifications are designed to optimize building capacity and increase the number of individuals that can be evacuated within a travel time considered relatively safe, in accordance with established standards for evacuation time during a tsunami event.

Table 7. Table of access time for proposed TEBs

Building	Access Time (minutes)	Number Evacuated (people)	Maximum TEB Capacity (people)
TEB 1	0 – 5	205	1829

Building	Access Time (minutes)	Number Evacuated (people)	Maximum TEB Capacity (people)
	5 – 17	385	
	17 – 22	115	
		705	
TEB 2	0 – 5	35	2029
	5 – 17	520	
	17 – 22	432	
		987	
TEB 3	0 – 5	15	480
	5 – 17	254	
	17 – 22	178	
		447	
TEB 4	0 – 5	70	1470
	5 – 17	620	
	17 – 22	574	
		1264	
KTEB1	0 – 5	35	2000
	5 – 17	710	
	17 – 22	465	
		1210	
KTEB2	0 – 5	45	2000
	5 – 17	740	
	17 – 22	425	
		1210	
KTEB3	0 – 5	225	2000
	5 – 17	470	
	17 – 22	10	
		705	
Total Number of Proposed TEBs		**6528**	**11808**

The simulation involving the introduction of three additional temporary evacuation buildings (TEBs) yielded outcomes detailing the coverage of various occupancy buildings and their associated access times, as illustrated in the table above. Each of the three suggested TEB candidates is designed with a total capacity of 2000 individuals, distributed across five floors. Specifically, floors 2-4 of the building can accommodate up to 1500 people, while the ground floor has a capacity for 500 individuals.

The cumulative capacity of both the recently proposed temporary evacuation building (TEB) candidates and the pre-existing TEBs amounts to 11,808 individuals. This figure, however, does not incorporate considerations for floors rendered unusable in the aftermath of a tsunami. In the event of such conditions, where the ground floor is untenable for evacuation due to flooding, the collective capacity of all TEBs and the suggested TEBs would be restricted to accommodating 8,535 individuals in Table 8. Despite this limitation, the specified count remains within the parameters of a safe number of individuals capable of evacuation within the nearest travel time.

Table 8. Table of proposed TEB locations and reach

Building	Building capacity (people)	Floor of building (people)	Reachable Village
TEB 1	1218	611	Deah Glumpang
TEB 2	1332	697	Ulhe lheu, Deah Baro
TEB 3	320	160	Lambhung

Building	Building capacity (people)	Floor of building (people)	Reachable Village
TEB 4	1165	305	Alue Deah Tengoh
KTEB 1	1500	500	Cot Lamkeuweh
KTEB 2	1500	500	Blang Oi
KTEB 3	1500	500	Deah Glumpang, Alue Deah Tengoh
Total	**8535**	**3273**	

3. CONCLUSION

Drawing upon the findings and discourse presented in this research, it is evident that effective tsunami mitigation necessitates thorough planning and analysis before, during, and after a disaster event. The escalating population size introduces dynamics that necessitate adjustments in the construction of facilities and determination of evacuation routes. The initial four Temporary Evacuation Building (TEB) facilities prove inadequate when considering the forecasted population growth of 6,528 individuals annually. As a preventive measure, the proposal advocates the construction of three additional TEB candidates, strategically positioned to cover the demographic segment not served by existing TEBs. The introduction of these TEBs instigates alterations in both the overall TEB capacity and the travel time to the nearest TEB, ensuring adherence to the designated allocation time of less than 22 minutes. The maximum capacity achievable from all TEBs, assuming the ground floor remains unaffected by tsunami inundation, is 11,808 people. In the event of the first floor being flooded, the capacity is limited to 8,535 individuals due to water overflow.

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