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Spatial modeling of tsunami for evacuation planning in Ciletuh Bay, Sukabumi, West Java

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Abstract. Indonesia is a country located at the meeting of three tectonic plates. This condition makes Indonesia a disaster-prone region, especially caused by the movement of tectonic plates, one of which is the tsunami. Several tsunami occurs were recorded in Indonesia. Tsunami occur on a large scale and causes losses, both environmental damage and fatalities. Therefore, evacuation planning is needed to minimize the number of fatalities when a tsunami occurs. This study aims to find out the potential threat of tsunami hazard in Ciletuh Bay and analyze evacuation planning in the region. The method used in this research is the spatial modeling method which is divided into tsunami inundation modeling, population distribution, and estimated evacuation travel time. The result of this study is that potential tsunami hazard in Ciwaru Village id found in two hamlets with an area of 104.63 Ha. A total of 590 exposed residents can evacuate within 0 – 15 minutes. The selection of evacuation routes with the fastest travel time is needed so that residents can reach the evacuation collection point before the tsunami arrives. The availability of road access in the hamlet makes it easier for residents in tsunami-exposed areas to reach evacuation gathering points.

1. Introduction

Indonesia is a country located at the meeting of three tectonic plates. The three plates are the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate. The Pacific Plate is located in the northern part of Maluku and Papua, while the Eurasian And Indo-Australian Plates collide in the regions off the coast of Java, Sumatra, and Nusa Tenggara. This condition makes Indonesia a disaster-prone region, especially caused by the movement of tectonic plates that can cause collisions between plates. Collisions between these plates can cause tectonic earthquakes. Earthquakes located on the seafloor trigger a tsunami if the earthquake has considerable strength.

Tsunami becomes one of the disasters with low frequency but great impact on exposed areas [1]. Tsunami events have occurred in various parts of the world for a long time but the impact of this disaster is still difficult to avoid. Therefore, research on tsunamis in various regions of the world is carried out to minimize the impact of the disaster. One of the tsunami-prone areas is the southern waters of Java Island. This is due to the condition of the southern waters of Java Island directly to the Indian Ocean [2]. One of the southern waters of Java Island is the coast in Sukabumi Regency. The potential for tsunami on the coast of Sukabumi is triggered by the active fault Cimandiri. Cimandiri active fault has a rising fault activity that has the potential to be the source route of the earthquake [3]. Several areas are included in the tsunami-prone area, one of which is the Ciletuh Bay. Beaches that do not have protection



such as mangroves, coconuts, and other coastal forests have the potential for a larger tsunami due to no wave barriers coming [4].

The process of evacuating people from tsunami-exposed areas to safe evacuation sites is a top priority during tsunami warnings. Between earthquakes and tsunamis that occur there is usually a time lag that can be used to evacuate themselves. Education related to the routes and evacuation places outside the tsunami exposed areas to the community must be done properly to minimize the death toll in the event. The determination of evacuation routes and places can refer to several things such as the estimated time of the tsunami coming, the speed at which people save themselves, and the capacity of the evacuation site. To get planning evacuation routes, a spatial system can be used to support decision making. Geographic Information Systems (GIS) can help make decisions regarding some of the things that were injured during the evacuation process, such as the extent to which tsunami waves reached land, which routes to go, and evacuation places that could be intended to save themselves. This research aims to analyze the potential tsunami hazard threat that occurred in Ciletuh Bay and determine evacuation planning based on modeling to be made.

2. Method

The method used in this research is spatial modeling based on Geographic Information System. Spatial modeling in GIS can help provide the simulation of emergency conditions with various scenarios so that data can be obtained for overall disaster mitigation. The modeling used is tsunami inundation modeling, population distribution, and estimated evacuation time. To find out the best evacuation route, network analysis is carried out. The combination of modeling in this study can be used to find out the evacuation planning in Ciletuh Bay.

Data processing of tsunami inundation area modeling refers to modeling techniques used by BNPB [5]. The distribution of affected areas is made from data processing with mathematical calculations developed by Berryman [6]. Berryman's method is based on the calculation of tsunami height loss every 1-meter distance of puddle height based on the distance to slope and surface roughness. This method helps for spatial analysis of tsunami exposure.

$H_{loss} = \left(\frac{167 n^2}{H_0^{1/3}} \right) + 5 \sin S$	Description
	H_{loss} : loss of tsunami height per 1 meter delay distance
	n : coefficient of surface roughness
	H_0 : tsunami wave height on the shoreline (m)
	S : the size of the surface slope (degrees)

The population is used for modeling the distribution of the population by processing the number of inhabitants per village and land use. Population distribution modeling is a combination of population data in the village and the distribution of settlements. Population data are obtained from statistical and census data. The right method to use in population distribution modeling in this study is to use the concept of dasymetric mapping [7].

$X_d = \sum_{i=1}^n P_i$	Description
$P_i = \sum_{j=1}^n P_{ij}$	X_d : Number of populations in administration unit
$P_{ij} = \frac{S_{ij}}{\sum_{i,j=1}^n S_{ij}} \cdot X_d$	P_i : The number of populations in all settlements in each village
	P_{ij} : Number of populations in polygon j a polygon settlement
	S_{ij} : Area of polygon j a polygon settlement

Cost Distance Weighted (CWD) will be used in the calculation of evacuation travel time. In this method, Speed Conservation Value (SCV) will be used in calculating evacuation accessibility. The SCV value itself is the percentage value of the maximum speed obtained from the classification of land cover in each cell grid [8]. This method also required slope data classified in the form of percent units and land use data in the form of the raster. In the calculation of the travel time of this evacuation, the speed of movement used is the slowest speed of movement of refugees. According to the Asian Disaster Preparedness Center [9], the average speed of 1.2 m/s was used and considered more realistic for refugees. With the CWD method, there will be a period of evacuation distance needed by residents in the research area.

3. Result and Discussion

- *Modeling the Potential Hazard of Tsunami in Ciletuh Bay*

In modeling tsunami inundation in the Ciletuh Bay area in Ciwaru Village, it uses two scenarios of maximum tsunami wave potential on the coast. In the first scenario, the maximum wave potential in Ciletuh Bay is as high as 10 meters. This maximum wave potential refers to Regulation of the head of the Disaster Management Agency No. 2 in 2012 [10] about the maximum wave height on the Sukabumi coast is 10 meters. While the second scenario has the potential for maximum tsunami waves in Ciletuh Bay as high as 20 meters. In the second scenario, this is the worst-case scenario of tsunami altitude referring to the maximum potential tsunami altitude in the southern waters of Java Island. The height of the tsunami wave of 20 meters is based on research in 2020 related to tsunami modeling using earthquake records in the south of Java Island [11]. The existence of seismic gap, megathrust and active fault in the south of Java Island allows for tsunami with high waves.

In the tsunami wave scenario of 10 meters, the total tsunami-affected area reaches 57.74 ha. Tsunami-affected areas are further classified into three hazard classes, namely low hazard class, medium hazard class, and high hazard class. In the low hazard class, the affected area reaches 6.54 Ha. Tsunami-affected areas are included in the medium hazard class covering an area of 10.82 ha. Meanwhile, tsunami-affected areas are included in the high hazard class of 30.38 ha. Determination of classification of this hazard class refers to Perka BNPB 2/2012 . The low hazard class has a ≤ 1 inundation grade, a medium hazard class with a grade of $1 < \text{inundation} \leq 3$, and a high hazard class with a > 3 . In the second scenario with the potential for maximum tsunami waves as high as 20 meters, the area affected by the tsunami reaches 104.63 ha. In the low hazard class, the affected area reaches 5.17 ha. Tsunami-affected areas are included in the medium hazard class covering an area of 6.89 ha. Meanwhile, tsunami-affected areas are included in a high hazard class of 92.57 ha. For further analysis, the potential tsunami hazard used is a wave height scenario of 20 meters considering this scenario is a worst-case scenario with the potential for maximum tsunami waves.

From the modeling results, we can find out the extent to which the tsunami will damage the area in Ciwaru Village. The absence of coastal forests such as mangroves or coconuts along the coast of Ciletuh Bay caused the absence of barriers that can break the waves when a tsunami occurs. This resulted in the coverage of tsunami inundation areas in the region. As previously known, the shape of the coastline in the form of bays has a greater potential for tsunami height due to the accumulated waves of seawater to the coast. In addition to being influenced by land use in Ciwaru Village, morphological conditions in this village also affect the range of tsunami inundation. Ciwaru village is a lowland area with an altitude of 0-334 meters above sea level. The area is dominated by lowland, except the eastern part of the area which is a hilly area that belongs to the Darma Hills area. Radius 1 km from the shoreline has an altitude of 0-100 meters above sea level. In addition to altitude, the slope of slopes in this region is quite sloping between 0° - 61.4° . The physical condition of this area plus the absence of coastal forests or embankments on the coast makes the reach of tsunami puddles widespread due to the absence of barriers or tsunami breakwaters that come to hit the mainland.

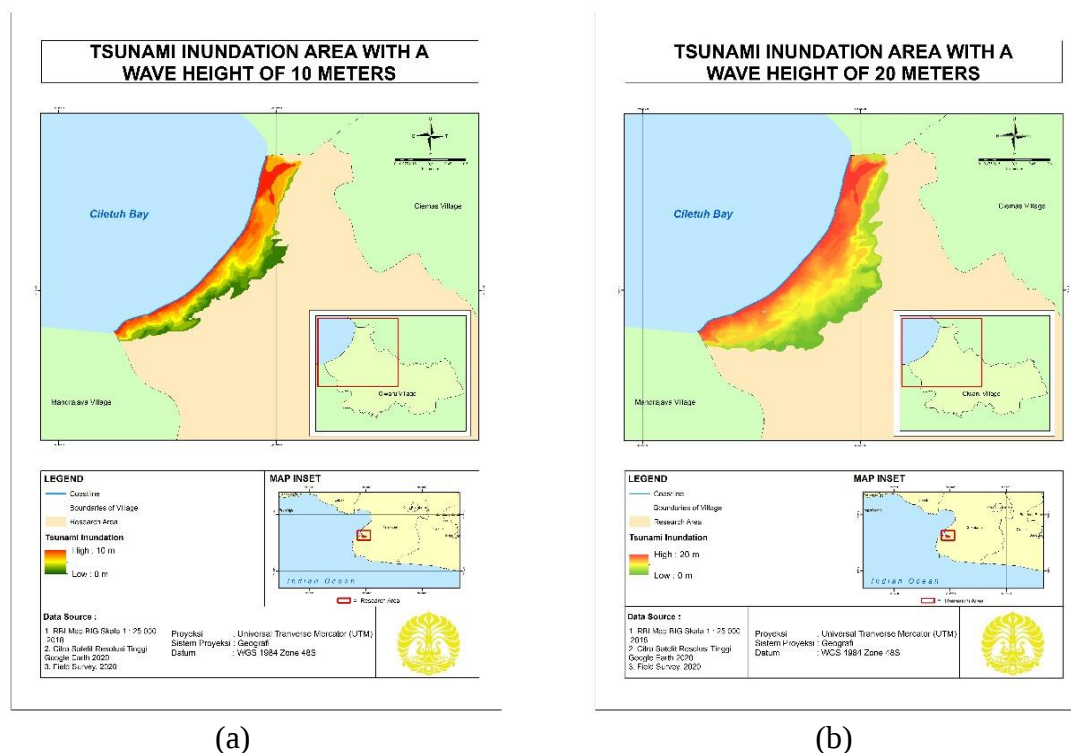


Figure 1. Map of tsunami inundation areas of 10-meter (a) and 20-meter (b).

- *Population in Tsunami-Exposed Area*

Data processing of potential tsunami hazard threats and population distribution can provide information on the number of people exposed to tsunamis. The people who were exposed to the tsunami were residents who were in the area of tsunami inundation. From the data processing, 590 people were found in tsunami-exposed areas. The number is indigenous in Ciwaru Village. Most of the people in the area are fishermen or traders who sell along Palangpang Beach. In addition to the locals, data on the number of tourists is also needed considering Ciwaru Village is included in the Ciletuh Geopark area. Several tourist attractions attract tourists, such as Palangpang Beach, Cimarinjung Waterfall, Cikanteh Waterfall, and Sodong Waterfall. Based on data from the Pakidulan Sukabumi Association (PAPSI), the number of tourists can reach 819 people [12]. The tourist data is used in the evacuation plan considering that most of the inns are in exposed areas. Also, Palangpang Beach is one of the tourist attractions that attract visitors. The area of tourist attractions included in the tsunami-exposed areas makes the number of tourists also a priority for evacuation to minimize fatalities when the tsunami occurs.

The area exposed to tsunami inundation reaches 600 meters from the shoreline. Meanwhile, residents who are in areas 1 km away from the coastline are still included in the population with high vulnerability. Therefore, evacuation planning is not only focused on residents in exposed areas but also on residents who are in the area 1 km from the coastline. This condition caused the number of people who had to be evacuated not only 590 people who were in the area exposed. The total number of people who are the priority of evacuation as many as 2,143 people spread across two hamlets, namely Tegalcaringin Hamlet and Gunungbatu Hamlet.

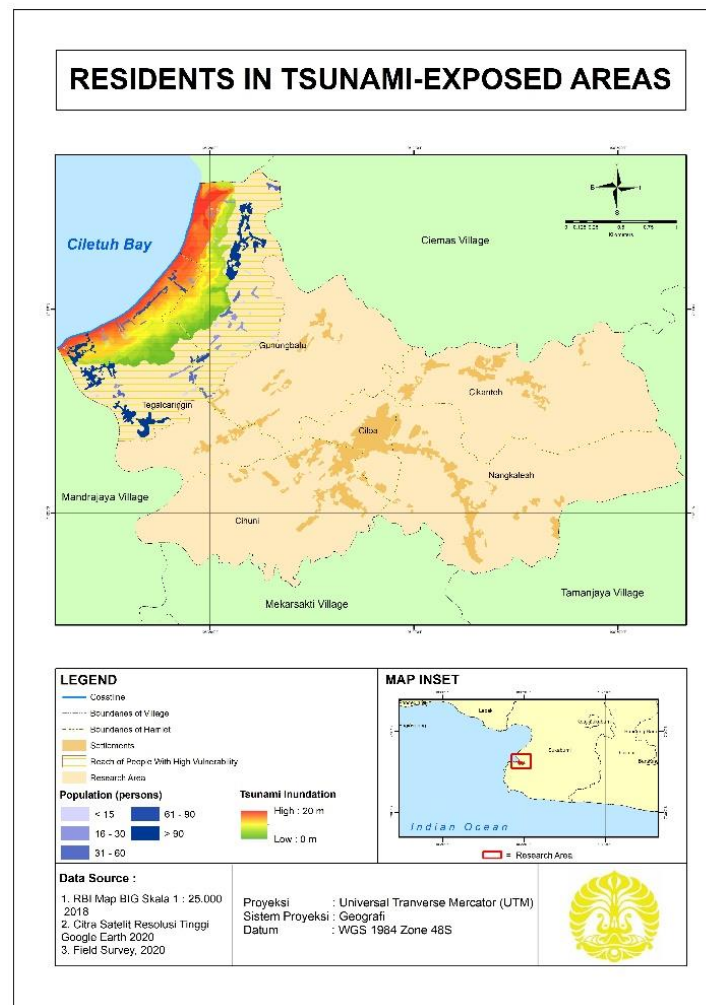


Figure 2. Map of Population in Tsunami-Exposed Area.

- *Estimated Evacuation Travel Time*

Evacuation time in this research is obtained from data processing by the Cost Distance method. The method uses land-use data and slopes that have been weighted by the Speed Conservation Value (SCV). From the results of the data processing, the maximum time needed for evacuation by the arrival time of the tsunami on the coast of Sukabumi Regency is 25 minutes.

After knowing the estimated travel time of tsunami evacuation in Ciletuh Bay can also be known the number of refugees based on the time of evacuation. The analysis was obtained from a combination of estimated evacuation time and distribution of residents in exposed areas. The estimated evacuation time in this area is influenced by the SCV value factor in each land use. Evacuation time is classified into 5 classes, namely minutes to 0-5, minutes to 5-10, minutes to 10-15, minutes to 15-20, and minutes to 20-25. In the first 5 minutes, 269 people could be evacuated from exposed areas to safe zones. The presence of roads with slopes that ramps help accelerate the evacuation of this area. Furthermore, a total of 266 people can be evacuated in the next 5 minutes with an estimated evacuation time of 5-10 minutes. In the estimated evacuation time of 10-15 minutes, there are as many as 55 people who can evacuate. This resident is located in the north of Ciwaru Village. The length of time of evacuation is caused because the slope in the north of the village is steeper than the southern region. All residents of exposed areas were able to evacuate before the tsunami arrived in the Teluk Ciletuh area. The existence of an adequate road network helps facilitate residents in the process of self-evaluation.

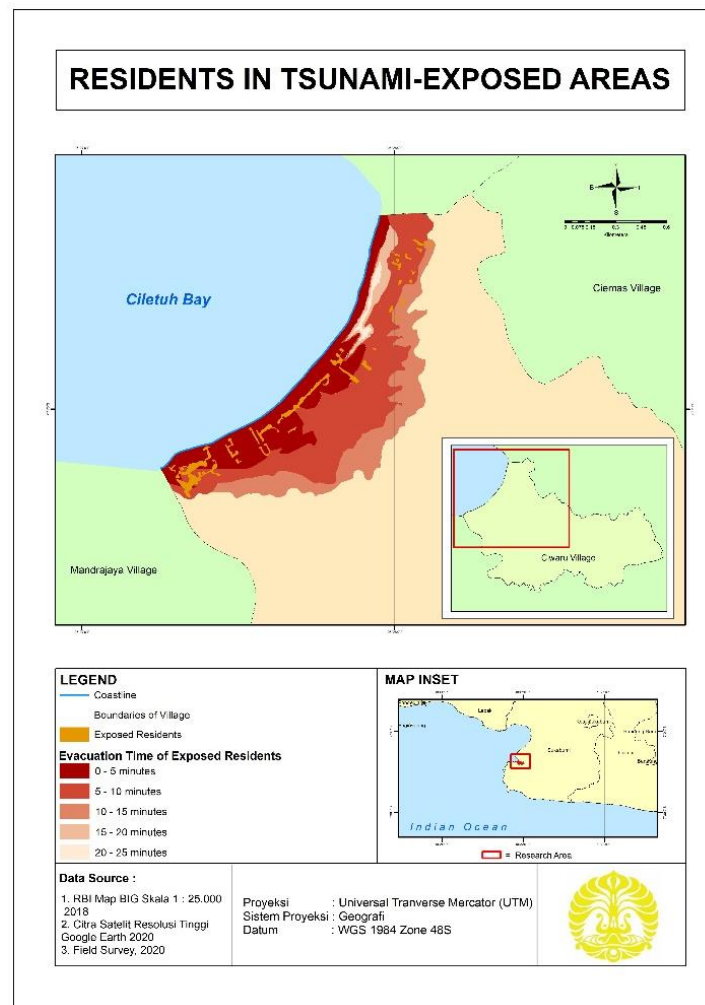


Figure 3. Population Map of Exposed Areas with Estimated Tsunami Evacuation Time.

- *Determination of Evacuation Routes in Tegalcaringin and Gunungbatu Hamlets*

There are five evacuation gathering points, namely Darma Peak, Pasir Haur, Cimarunjung Waterfall area, Ciwaru Village Hall, and MTs Al - Furqon. With five evacuation points, locals have a more diverse choice and can reduce the buildup of refugees in one place. The evacuation route to Cimarunjung Waterfall and Darma Peak area is parallel to the shoreline. This is due to the river crossing the area. In addition, the absence of other roads other than the main road makes the road the only road that can be taken by refugees to the Cimarunjung Waterfall and Darma Peak area.

Tegalcaringin Hamlet is one of the hamlets whose area is partly exposed to the tsunami. Its location directly adjacent to the sea makes this area very vulnerable to tsunami. The physical condition of the area which is a lowland with an altitude of fewer than 100 meters above sea level with sloping slopes is one of the factors causing some of these areas to be exposed to tsunamis. To minimize the death toll when the tsunami occurred, it is necessary to plan the evacuation route of residents in Tegalcaringin Hamlet. Residents in Tegalcaringin Hamlet can evacuate to a safer place, namely cimarunjung waterfall area, Darma Peak, SMAN 1 Ciemas, Ciwaru Village Hall, and MTs Al-Furqon. Each evacuation collection point has different mileage and travel times. To get to the Cimarunjung Waterfall area, the population takes 8 minutes. Residents can evacuate to Darma Peak in 15 minutes. To get to the gathering point of SMAN 1 Ciemas, Ciwaru Village Hall, and MTs Al-Furqon, there are two lines that can be used. The first line through the bridge and the second line is an alternative route if the bridge in the first

lane is damaged so that it cannot be passed by residents for evacuation. The distance and time required by residents for evacuation can be seen after table 1.

Gunungbatu Hamlet is one of the areas directly adjacent to the sea. The physical condition of this area in the form of lowland with an altitude of fewer than 100 meters above sea level and a sloping slope caused some areas in this hamlet to be exposed to tsunamis. Planning evacuation routes in this area are needed to minimize fatalities when a tsunami occurs. Residents in Gunungbatu Hamlets can evacuate to the existing gathering point. To get to the gathering point in the Cimarunjung Waterfall area only takes 4 minutes from the settlement area in this hamlet. Residents can also evacuate to Darma Peak with a travel time of 10 minutes. In addition, residents in Gunungbatu Hamlet can also evacuate to the gathering point in the eastern area of this village. Residents can evacuate to Ciwaru village hall gathering point takes 12 minutes. The travel time needed to get to the evacuation point at MTs Al-Furqon is 13 minutes. Meanwhile, to get to the gathering point at SMAN 1 Ciemas requires an evacuation time of 13 minutes as well. The distance and time required by residents for evacuation can be seen after table 2.

Table 1. Distance and Travel Time of The Evacuation of Tegalcaringin Villagers.

Origin	Evacuation Gathering Point	Distance (km)	Travel Time (minutes)
Tegalcaringin Hamlet	Cimarunjung Waterfall	2,7	8
	Darma Peak	4,8	15
	Ciwaru Village Hall	3,7	11
	SMAN 1 Ciemas	3,8	11
	MTS Al-Furqon	4,3	13
	Ciwaru Village Hall (Alternative routes without crossing the bridge)	7	20
	SMAN 1 Ciemas (Alternative routes without crossing the bridge)	7,2	21
	MTS Al-Furqon (Alternative routes without crossing the bridge)	7,5	22

Table 2. Distance and Travel Time of The Evacuation of Gunungbatu Villagers.

Origin	Evacuation Gathering Point	Distance (km)	Travel Time (minutes)
Gunungbatu Hamlet	Cimarunjung Waterfall	1,4	4
	Darma Peak	3,5	10
	Ciwaru Village Hall	4	12
	SMAN 1 Ciemas	4,2	13
	MTS Al-Furqon	4,5	13

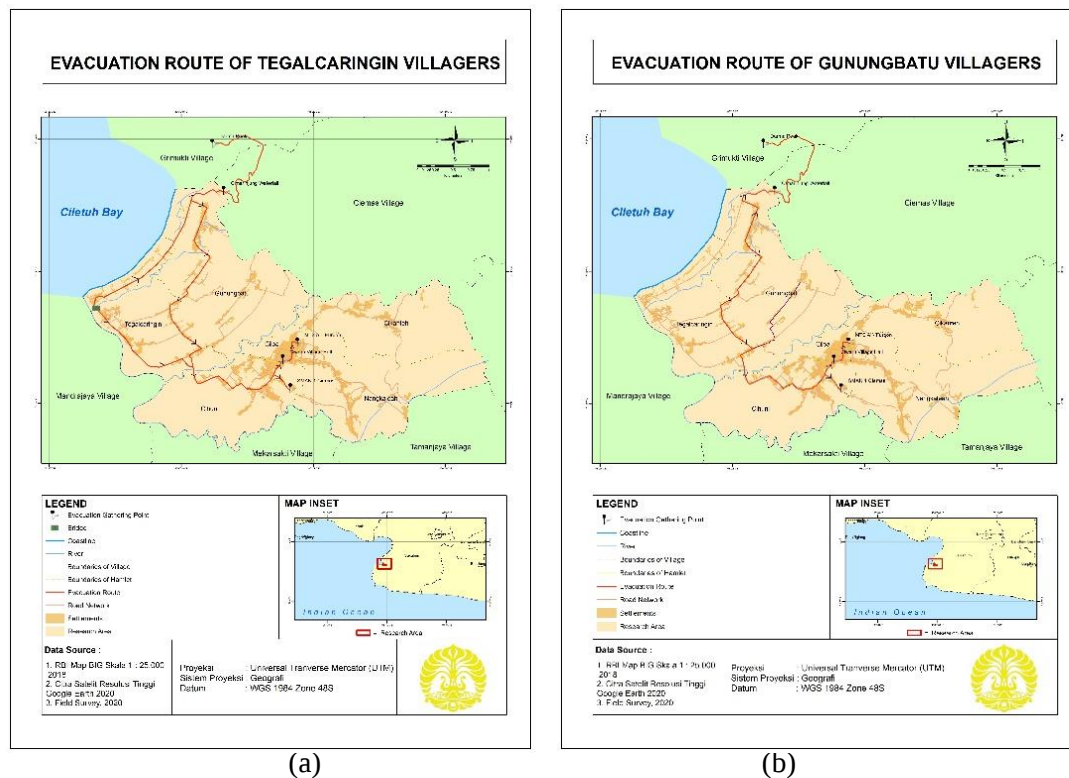


Figure 4. Map of The Evacuation Route of Tegalcaringin Villagers (a) and Gunungbatu (b).

4. Conclusion

The potential of tsunami hazard in Ciletuh Bay is influenced by the physical condition of the region. Ciwaru village has a slope that is quite sloping with a height of 0-334 meters above sea level affecting the reach of tsunami inundation areas. With a maximum tsunami wave height scenario of 20 meters, the range of tsunami inundation area reaches 104.63 ha. The absence of coastal forests such as mangroves or coconuts along the research area caused the absence of barriers that can break the waves when a tsunami occurs. This condition caused the widespread distribution of inundation areas in Ciwaru Village. There are two areas that the priority of evacuation, namely Tegalcaringin Hamlet and Gunungbatu Hamlet. These two hamlets are areas that have the potential tsunami hazard of Ciletuh Bay. Based on the data processing that has been done, the population exposed in both areas reached 590 people. All residents in exposed areas can evacuate within 0-15 minutes. The selection of evacuation routes with the fastest travel time is needed so that residents can reach the evacuation collection point before the tsunami arrives. The availability of road access in the hamlet makes it easy for residents in tsunami-exposed areas to reach the designated evacuation collection point.

Acknowledgement

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