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Tsunami evacuation modelling for region capacity evaluation in Panimbang, Pandeglang Regency, Indonesia

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Abstract

Panimbang sub-district, located in the subduction zone of the Indo-Australian plate and directly facing Mount Anak Krakatau, is highly vulnerable to tsunami hazards. The region's geographic location and its coastal topography make it particularly susceptible to the devastating impacts of tsunamis. This study assesses the region's preparedness to manage tsunami risks using Geographic Information System (GIS) tools to model evacuation routes and estimate potential inundation areas. The research evaluates the effectiveness of the region's evacuation capacity, considering critical factors such as population distribution, land cover, and the time required for residents to evacuate safely.

The study's findings indicate that 74.91% of the 512.73 hectares of residential area in Panimbang is at significant risk of tsunami impact, potentially affecting approximately 38,723 people. This high level of exposure underscores the urgent need for tailored evacuation strategies, particularly in densely populated areas, to minimize the risk of casualties. The analysis also highlights the importance of enhancing infrastructure and disaster preparedness plans to increase the resilience of communities most vulnerable to tsunami threats. The research provides valuable insights into the critical elements of tsunami disaster management. It can serve as a crucial reference for future studies focused on improving evacuation routes, shelter planning, and other essential aspects of critical infrastructure. By addressing these areas, future efforts can more effectively safeguard the population in tsunami-prone regions, ensuring a more efficient and organized disaster response that significantly reduces the potential for loss of life and property.

Keywords: *Tsunami, evacuation time, population exposure, Geographic Information System (GIS), evacuation capacity*

Introduction

The existence of tectonic plate collisions in subduction zones as a natural mechanism that causes submarine earthquakes is the main trigger of tsunami disasters (Suppasri et al., 2017). Tsunami disasters caused by submarine earthquakes are categorized as natural disasters with high destructiveness and are difficult to predict (Ramadan, 2018). This phenomenon in recent years has troubled the world community because of the impact it causes, including the Palembang community. The latest records about the tsunami on 22 December 2018 show that the total number of deaths could reach approximately 437 people (BNPB, 2018). Panimbang sub-district is included in the area that is in the subduction zone of the Indo-Australian plate and directly faces Mount Anak Krakatau (Grilli et al., 2019).

This condition causes the Panimbang sub-district to be prone to natural disasters, especially Tsunamis. The Panimbang area can be hit by an earthquake magnitude of 9.1 on the Richter scale and a potential tsunami height of up to 20.2 meters (Widiyantoro et al., 2020). Panimbang sub-district is a water area on the west coast of Banten that directly faces the Sunda Strait and has a morphological condition allowing it to experience the accumulation mechanism of sea waves towards the mainland. This condition reinforces the potential risk/significant impact that may arise from a tsunami disaster (Pranantyo et al., 2020). A review of the capacity readiness of the Panimbang sub-district toward the potential for a tsunami disaster is critical as a form of implementing disaster management policies.

The need for this study is highlighted by gaps in current disaster preparedness strategies. While substantial research has been conducted on tsunami risk assessment and early warning systems, there is a pressing need for localized evacuation planning and capacity assessment. Existing studies, such as those by Horspool et al. (2014), have modeled potential tsunami heights but often lack specific evacuation scenarios tailored to vulnerable communities. Additionally, international frameworks like the Sendai Framework for Disaster Risk Reduction emphasize the importance of local-level resilience and preparedness, which this study aims to address by providing a detailed analysis of evacuation capacity and readiness in the Panimbang sub-district.

The potential for a tsunami can be identified from a study of physical characteristics (Romano et al., 2020) and the geographical location of an area (Hermon, 2019). The morphological condition of the coast is one of the physical factors that influence the height of a tsunami wave when it reaches land (Farahdita et al., 2020). Tsunami waves get more prominent as the intensity increases in a relatively sloping coastal area with a low coastline, compared to a coast that is relatively deep and steep or has a high coastline slope (Ren, 2020). The potential for a tsunami may increase if the morphology of the coast with a sloping bay coastline does not have protective plants such as mangroves, coconut, warm trees and other coastal forests (Majid et al, 2020).

The evacuation of people living in risk areas is a significant priority that must be carried out when the tsunami early warning has been received. This is because the period from the warning until the tsunami wave reaches the land is very short (Wang et al., 2019), so all the necessary preparations must be determined in advance. A formal evacuation plan is the basis for providing the community with reference, direction, and information. The plan explains the steps and actions needed to ensure a smooth emergency evacuation process from the hazard location before the disaster strikes. The main task of a planner when a tsunami occurs is to ensure the speed and safety of the evacuation process. Tsunami emergency evacuation planning requires a dynamic review of the community capacity (condition) and the availability of various environmental resources (Muhammad et al., 2017).

The primary objectives of this study are threefold: first, to assess the tsunami impact on the Panimbang sub-district by examining its physical and geographical characteristics; second, to model evacuation routes considering the maximum potential tsunami height; and third, to evaluate the region’s readiness and capacity for effective evacuation, focusing on factors such as population distribution, land cover, and travel time. By addressing these objectives, the study aims to fill existing gaps in evacuation planning and contribute to the development of more effective tsunami disaster management strategies.

The conceptual framework of this study centers on key terms such as risk, impact, and capacity. Risk in this context refers to the likelihood of a tsunami occurring and its potential consequences on the population and infrastructure. Impact denotes the extent of damage or disruption that a tsunami could cause, while capacity refers to the region’s ability to effectively manage and mitigate these impacts through preparedness and response mechanisms. Understanding these elements is crucial for comprehensively assessing the tsunami risks in Panimbang and developing targeted mitigation strategies.

Three methodologies are combined in this study, and the aim is to model the tsunami evacuation route by calculating the maximum potential value of a tsunami wave using the cost distance and speed conservation value. It aims to produce an overview of the study area's exposure areas and safe zones. A scenario of a maximum tsunami height of 15 meters with a tsunami arrival time scenario of 25 minutes is also applied in this study. The time assumption is adjusted to the results of tsunami modeling carried out by tsunami experts determined by (BNPB, 2012). The calculation includes the area's exposure to the maximum potential waves, population distribution analysis, and the travel time for evacuation in the study area. The data that has been obtained are then interpreted using the Geographical Information System spatial modeling. Spatial modeling with Geographic Information Systems was chosen because it integrates various factors to obtain comprehensive results (Arabameri et al., 2018). This analysis provides an overview of the Panimbang region's readiness to deal with a tsunami disaster. Furthermore, it can be used as evaluation material for the applicable disaster management system (Petrov et al., 2020). Further, this research is expected to become information and reference for the government and local communities in determining an effective and efficient tsunami disaster mitigation strategy.

Materials and Methods

This study employed a multi-faceted approach to tsunami evacuation modeling that draws on methodologies used both within Indonesia and internationally. In Indonesia, tsunami evacuation modeling typically relies on data and approaches developed by national agencies such as the National Disaster Management Authority (BNPB). These approaches emphasize the use of local geographic and demographic data, focusing on region-specific factors like population density and coastal topography. Internationally, methodologies such as those proposed by Horspool et al. (2014) and Wood et al. (2012) are prevalent, especially in regions with similar geological and coastal features. These methods provide robust frameworks for modeling tsunami risk, but they often require adaptation to fit the specific characteristics of different regions.

In this study, we integrated these existing methodologies to develop a tailored approach for the Panimbang sub-district. We selected the Cost Weighted Distance and Speed Conservation Value (SCV) calculations as the core elements of our modeling approach. The choice of these elements was driven by their ability to account for the unique geographical features and population distribution of Panimbang. The Cost Weighted Distance method is particularly effective in modeling evacuation routes by considering the varying difficulty of terrain, while the SCV calculation helps estimate realistic evacuation times based on land cover and slope. These methods were chosen because they provide a detailed and localized understanding of evacuation dynamics, which is crucial for accurate risk assessment and planning in this high-risk area.

The evacuation capacity modeling in units of time with a height of 15 meters was applied using the potential tsunami maximum height scenario (Horspool et al., 2014). There are three scenarios of tsunami height in the modeling by (Horspool et al., 2014), namely 7.5 meters, 15 meters, and 20 meters. This research used wave prediction with a height of 15 meters. The aim was to predict the impact of the highest waves that do not exceed the sub-district administrative boundary coverage. The assumption of the arrival time of waves on the shoreline used in this study was based on the estimated time set by the National Disaster Management Agency, which was 25 minutes.

The research area was done by Geographic Information System using ArcMAP to process elevation, slope, land cover, and population data. Elevation and slope data were sourced from DEMNAS (Digital Elevation Model Nasional) imagery, which provided detailed topographic information crucial for analyzing slope and terrain features. DEMNAS is a high-resolution digital elevation model developed by the Indonesian Geospatial Information Agency (BIG). It combines data from various sources, including LIDAR, IFSAR, and other satellite-based measurements, to comprehensively and accurately represent Indonesia's topography. The resolution of DEMNAS typically ranges from 0.27 to 8.1 meters, depending on the area, making it highly suitable for detailed terrain analysis in disaster-prone regions such as Panimbang. Necessary for analyzing slope and terrain features. Land use and land cover data were derived from Landsat 8 OLI TIRS satellite images, allowing us to classify and map different land cover types, such as forests, agricultural fields, and urban areas, which are critical for understanding the potential impact of a tsunami and planning evacuation routes. Population data was obtained from the 2018 census by the Central Statistics Agency of Pandeglang Regency. This data provided detailed insights into population distribution across the sub-district, enabling a more accurate assessment of the number of people at risk and the most densely populated areas. The results were then processed and analyzed to determine the evacuation capacity through spatial modelling. The flow chart is presented below for more detailed information.

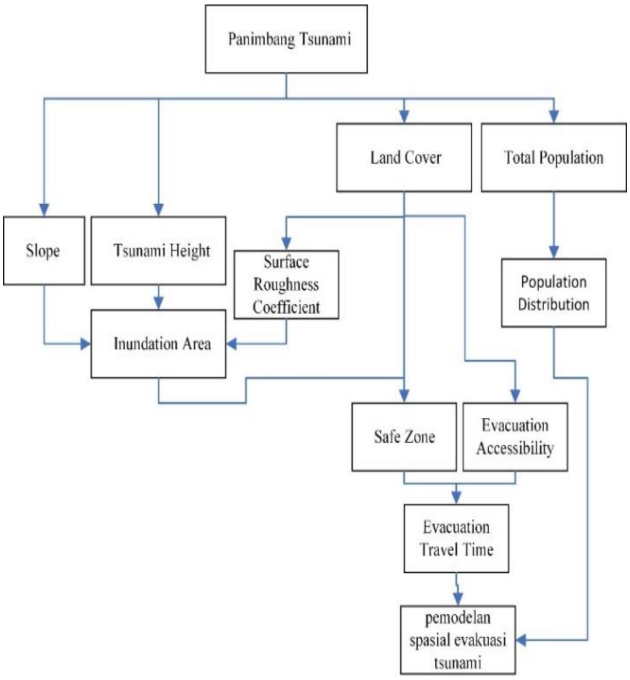

Figure 1. Research Flowchart

The data in this research was processed using GIS, which produced a form of processing in the form of spatial data that visualized the process being carried out (Sambah et al., In this study a tsunami modeling used was from (Perka, 2012) with formulation (Berryman, 2006) (Figure 2) and height data from the prediction by (Horspool et al., 2014). Referring to this formulation, the loss calculation was carried out based on the loss of the tsunami height every 1 meter. The data used in this research were sourced from SPOT and Landsat 8 images. This data was processed to produce the Hloss value before processing the calculation results until an estimate of the tsunami inundation area had been obtained (Berryman, 2006).

$$H_{loss} = \left(\frac{167\, n^2}{H_0{}^{1/3}}\right) + 5\, Sin\, S \qquad \text{(Supassri et al, 2017)}$$

H_{loss} = Loss of height every 1 meter to the unity of distance's slope

n = Surface roughness index

H_0 = Tsunami wave height

S = Slope elevation

Estimating the inundation area, the residential area, and the activity center and identifying which areas are affected and which are not can be identified. Population data are generally obtained as statistical tables and presented spatially referring to the administrative unit boundaries of an area (choropleth mapping) (Besançon et al., 2020). This method is considered inadequate in the spatial context of disasters, especially when describing how many people are in the tsunami-exposed area. Dasymetric mapping is an area-based thematic mapping method that produces more detailed spatial information (Khomarudin et al., 2010). The advantage of dasymetric mapping is its ability to produce a more realistic spatial distribution of the population than choropleth mapping. This applied concept can be classified as a top-down method of population distribution based on the distribution of settlements in the study area (Syahputra et al., 2019). This method is also known to be used by (Ali et al. 2020; Yulianto, 2014; Purnamasari, 2017). The following is an example of a calculation using the dasymetric method to measure population distribution.

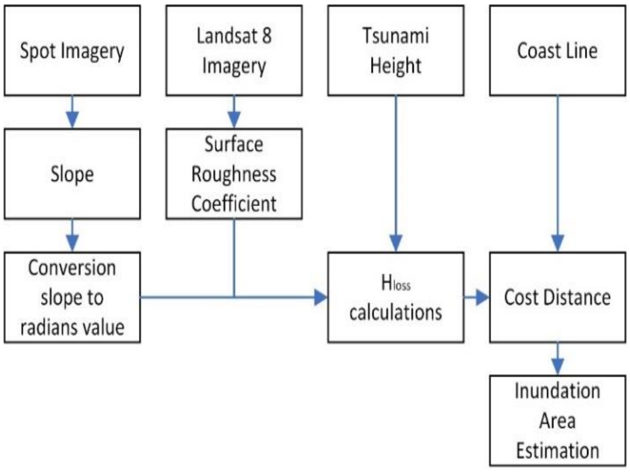

Figure 2. Modeling diagram of the inundation area

Figure 3 shows the data requirements for the population distribution mapping method. Data related to the population of each village and the distribution of settlements in the study area are the main variables in the population distribution modeling, as shown in Figures 3 (1) and 3 (3). Meanwhile, Figure 3 (2) shows that the measurement of population distribution is based on raster data, where the grid size in the measurement corresponds to the land cover raster, which is 1 meter. Figure 3 (4) calculates the area of each grid group in each village. According to the three data sets, each village's total settlement area is obtained, as shown in Figure 3 (5). The population of each residential grid in each village in the study area is calculated in Figure 3 (6). The calculation of the mathematical equation is shown in Equation 2, equation 3, and equation 4 (Khomarudin et al., 2010).

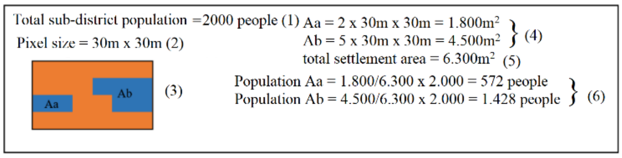
Total sub-district population =2000 people (1)
Pixel size = 30m x 30m (2)
Aa = 2 x 30m x 30m = 1.800m² }
Ab = 5 x 30m x 30m = 4.500m² } (4)
total settlement area = 6.300m² (5)
Population Aa = 1.800/6.300 x 2.000 = 572 people }
Population Ab = 4.500/6.300 x 2.000 = 1.428 people } (6)

Figure 3. The example of a population distribution mapping method

$$X_d = \sum_{i=l}^{n} P_i \, \mathrm{H_{loss}} = \left(\frac{167\mathrm{n}^2}{\mathrm{H_0}^{1/3}}\right) + 5\mathrm{SinS} \qquad (2)$$

$$P_i = \sum_{J=l}^{k} P_{ij} \, \mathrm{X_d} = \sum_{\mathrm{i=l}}^{\mathrm{n}} \mathrm{P_i} \, \mathrm{H_{loss}} = \left(\frac{167\mathrm{n}^2}{\mathrm{H_0}^{1/3}}\right) + 5\mathrm{SinS} \qquad (3)$$

$$P_{ij} = \frac{S_{ij}}{\sum_{j=l}^{k} S_{ij}} \, . W_{i.} X_d \qquad (4)$$

X_d = Number of people in administrative unit
Pi = Number of people in land use i
P_{ij} = Number of people in polygon j in land use i
S_{ii} = Size of polygon j in land use i

W_i = Weighting of land use $\sum_{i=l}^{n} W_i = 100\%$

K = Number of polygons in land use i
n = Number of Land use in village d

The evacuation time with the cost distance, or in this case ts,unami accessibility, is calculated based on the Speed Conservation Value (SCV) value. The calculation result shows the maximum velocity percentage value obtained from the land cover classification in each raster cell (Wood et al., 2012; Oliveira, 2020; Alvarez et al., 2018). Figure 4 shows the step chart for calculating the evacuation time.

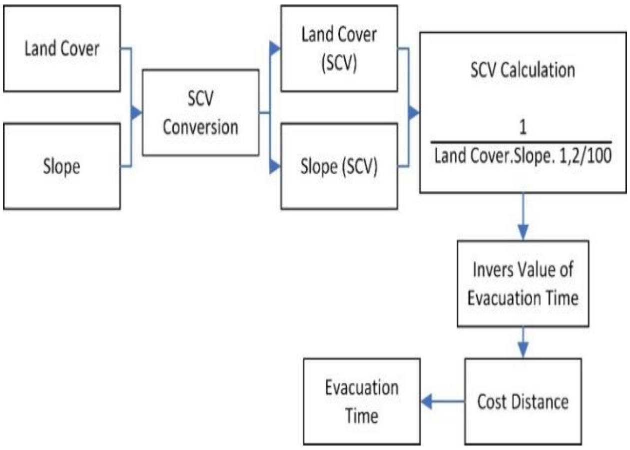

Figure 4. Modeling diagram of evacuation time

Source: (Widyaningrum, 2009)

The slowest movement speed of refugees during evacuation is also given in the evacuation modeling in this study (Widyaningrum, 2009). The results obtained showed that a value of 1.2 m/s was found to be more realistic for the majority of refugees. This value of 1.2 m/s was obtained from the average velocity of children aged 0-14 years in the evacuation, namely 1.06 m/s, productive age 1.33 m/s, and the elderly 0.93 m/s. (Kontar et al, 2016). The average value was used considering that the distribution of the population was generated evenly without taking into account age, so this value was used for modeling accessibility. The time span for evacuation in the study area was obtained based on the Cost Distance method (Kontar et al., 2016).

Results and discussion

Tsunami Inundation Area Modeling

The slope comparison variable in this study was obtained from DEM-NAS imagery, while the land cover identification was obtained from Landsat 8 OLI TIRS. The surface roughness index was obtained from these variables, which was then used in calculating the cost distance from the coastline (Faucher et al., 2020). According to (Berryman, 2006), it was explained that if the surface roughness index value in land cover identification is high, then the surface roughness index value will also be higher.

The surface roughness index is shown in the water flow flowing over the surface with rough and irregular topography (Berryman, 2006). Figure 5 provides a detailed visualization of the land cover types across the Panimbang sub-district. This figure is essential for contextualizing the study's results, as it shows the land cover types found in the Panimbang sub-district are watersheds, reservoirs, plantations, residential areas, open fields, rice fields, forests, and bushes that are particularly vulnerable to tsunami impact. As highlighted in the figure, the dense clustering of the residential regions in low-lying zones directly correlates with the high population exposure rates identified in this study. This spatial distribution is crucial because it identifies the specific areas where evacuation efforts must be prioritized, thus supporting the conclusion that targeted evacuation strategies are necessary.

Modelling by (Horspool et al., 2014) is divided into three tsunami height scenarios, which are 7.5 meters, 15 meters, and 20 meters. Meanwhile, in this study, the wave prediction used was a height of 15 meters. Figure 6 illustrates the predicted tsunami inundation areas. This figure is critical for understanding the spatial extent of tsunami impact, showing how the red zones—areas with the highest risk of inundation—coincide with densely populated regions. This height is chosen as it aims to predict the impact of the highest wave that does not exceed the sub-district administrative boundary coverage. The area of the Panimbang sub-district is 5523.7 Ha, of which 2007.34 Ha or 55.27% is the area exposed to the tsunami. Of the total area, the total residential area is 512.73 Ha, whereas the settlement area exposed to the tsunami is 384.08 Ha or 74.91%. The area with the most exposure is Mekarsari Village.In contrast, Mekarjaya Village has the smallest exposed area. An overview of the results of the tsunami exposure area is shown in Figure 6. The method used in the modeling to estimate the area of tsunami inundation is a method that has been tested for accuracy in (R. N. Majid et al., 2020), which discusses the estimation of tsunami area in the Pandeglang district, where there is also a modeling test compared to the tsunami event that occurred on 22 December 2018 with the results tsunami wave modeling at its farthest point is the same as the 2018 tsunami event.

These findings align with other studies conducted in similar coastal regions in Indonesia. For example, Pranantyo et al. (2020) conducted a study on the tsunami risk in the Sunda Strait and found that approximately 60% of the coastal areas were exposed to tsunami risk, with a significant proportion of the population living in these high-risk zones. Although the percentage of land at risk is somewhat lower than what was found in Panimbang, the overall exposure of the population is similar, indicating a consistent level of vulnerability across different regions of Indonesia.

Comparing these results internationally, the study by Horspool et al. (2014) in New Zealand also identified a substantial portion of the population as being at risk from tsunamis, particularly in regions with complex topography and dense population centers. Their study revealed that approximately 50-70% of the population in certain coastal areas was within tsunami hazard zones, which is comparable to the 74.91% exposure found in Panimbang. This consistency in population exposure across different geographies highlights the universal challenge of protecting large coastal populations from tsunami hazards.

Further comparison can be made with the results of Ren et al. (2020), who analyzed tsunami risk in the Tohoku region of Japan following the 2011 earthquake. Their study found that over 80% of the low-lying coastal areas were at risk of inundation, with significant implications for the densely populated coastal communities. Although the percentage of land at risk in Tohoku is slightly higher than that in Panimbang, the exposure of the population is similar, suggesting that both regions face considerable challenges in ensuring the safety of their residents during a tsunami event.

In the Indonesian context, Widiyantoro et al. (2020) examined the tsunami risk in South Java, where they found that 57% of the land area was at risk, with approximately 70% of the population living within these zones. This is closely comparable to the 55.27% of the land and 74.91% of the population found to be at risk in Panimbang. The slight differences in land area at risk may be attributed to variations in coastal topography and the distribution of population centers, but the overall pattern of vulnerability is consistent.

Figure 7 is an aerial photo of the 2018 tsunami-affected area (left). In Figure 7, the right is the result of image processing from the affected area (graduated color), compared with the model used (red line). In this study, the modeling results have high consistency; the tolerance given is due to changes in the earth's surface, which are hit by waves, thus changing the initial surface roughness value.

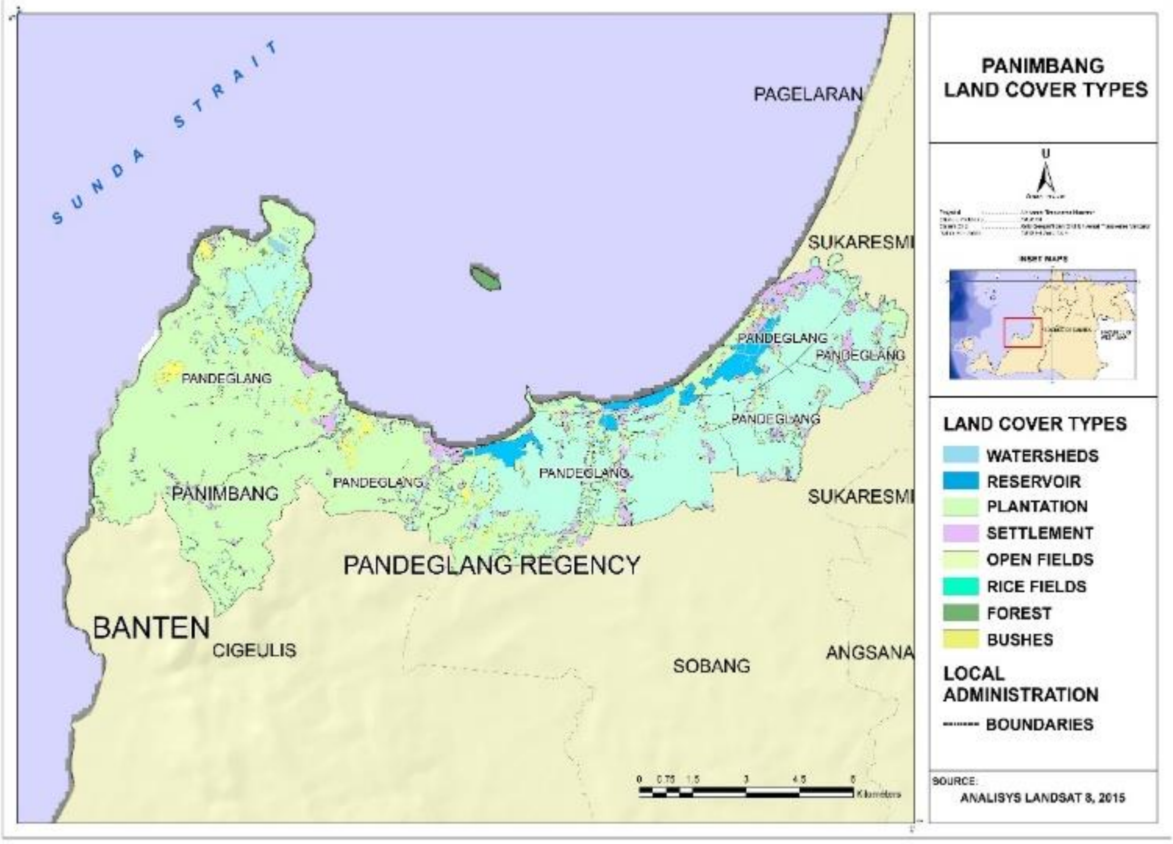

Figure 5. Type of Land Cover in Panimbang sub-district

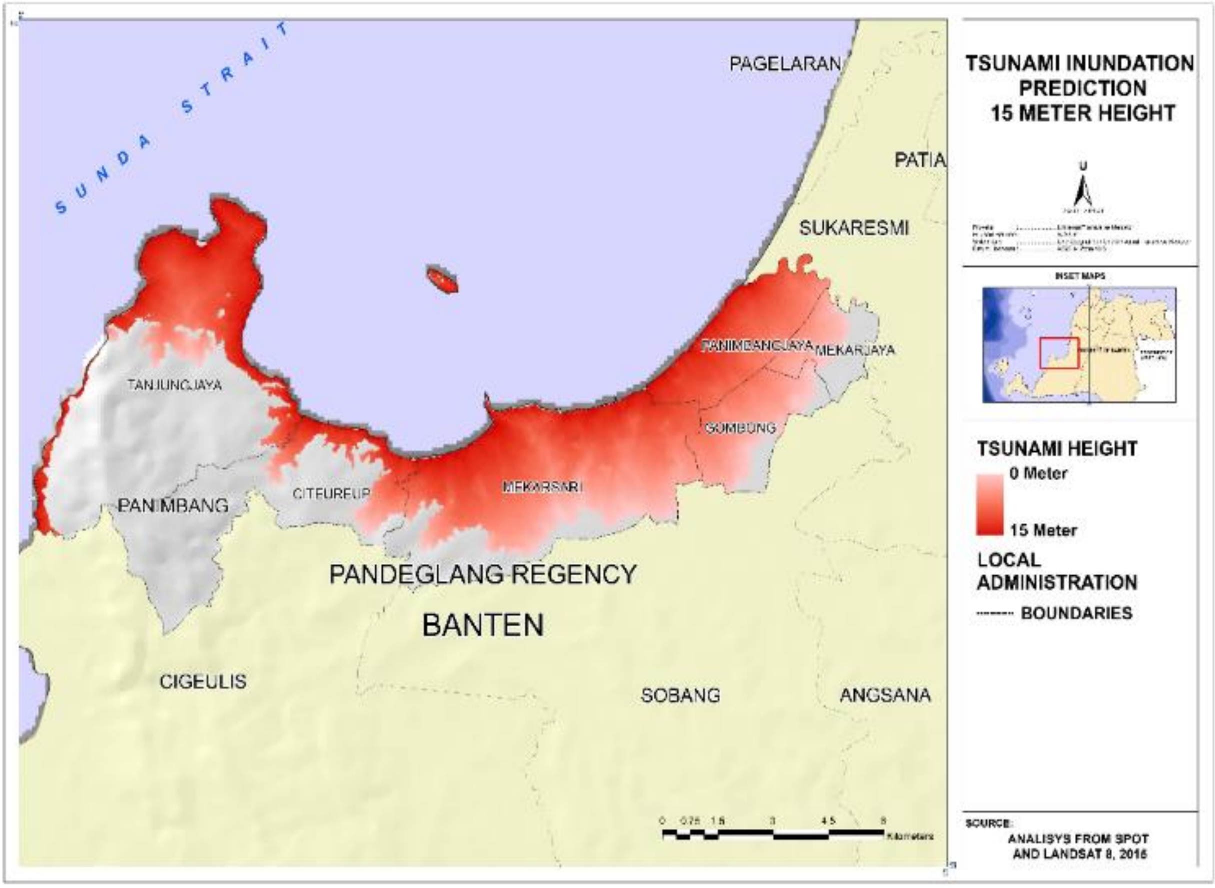

Figure 6. Predicted Tsunami Inundation at Height of 15 Meters

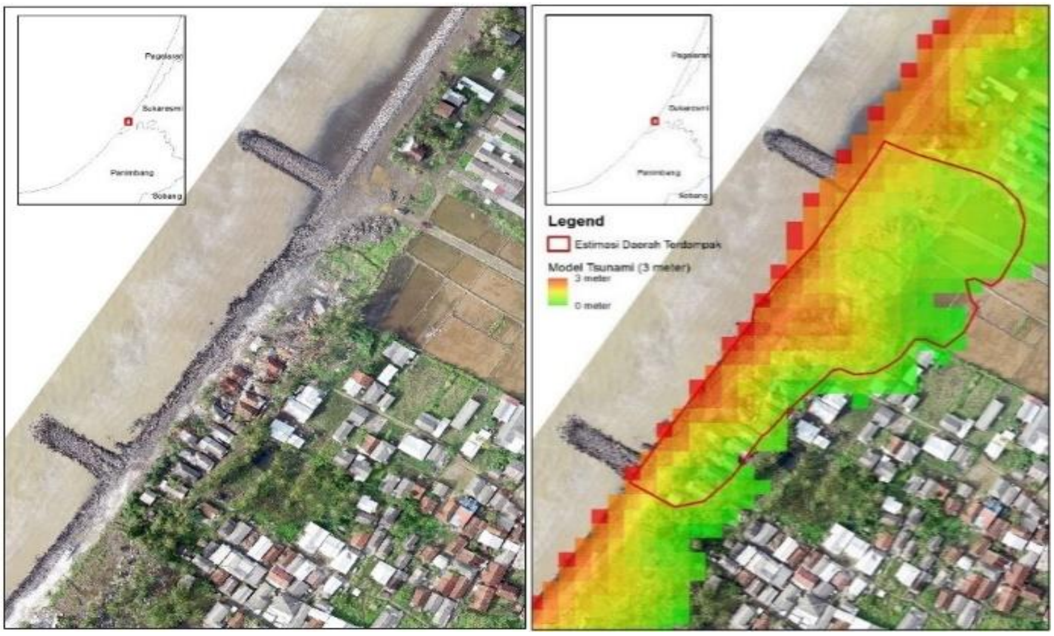

Figure 7. Comparison of the model used to the tsunami occurred on 22 December 2018 (.R. N. Majid et al, 2020)

Population Distribution

The 2018 census data was used to determine the total population in the Panimbang sub-district. The data comes from the Central Statistics Agency of Pandeglang Regency. This population census was used in population distribution modeling to determine the distribution of the population around the Panimbang sub-district. Distribution modeling was done by processing data on the population and distribution of village settlements in the Panimbang sub-district. In this case, The distribution of settlements results from land cover processing in the Panimbang sub-district. Figure 8 shows that the population density in the Panimbang sub-district has mixed results. The most densely populated areas are Panimbang Jaya Village, Mekarsari Village, and Citereup Village, with a population of 15,973; 11,204; and 9,276, respectively. On the other hand, residential areas with a moderate to low population are Tanjungjaya Village, Gombong Village, and Mekarjaya Village, with a total number of 7,200; 4,535; and 3,502 residents, respectively.

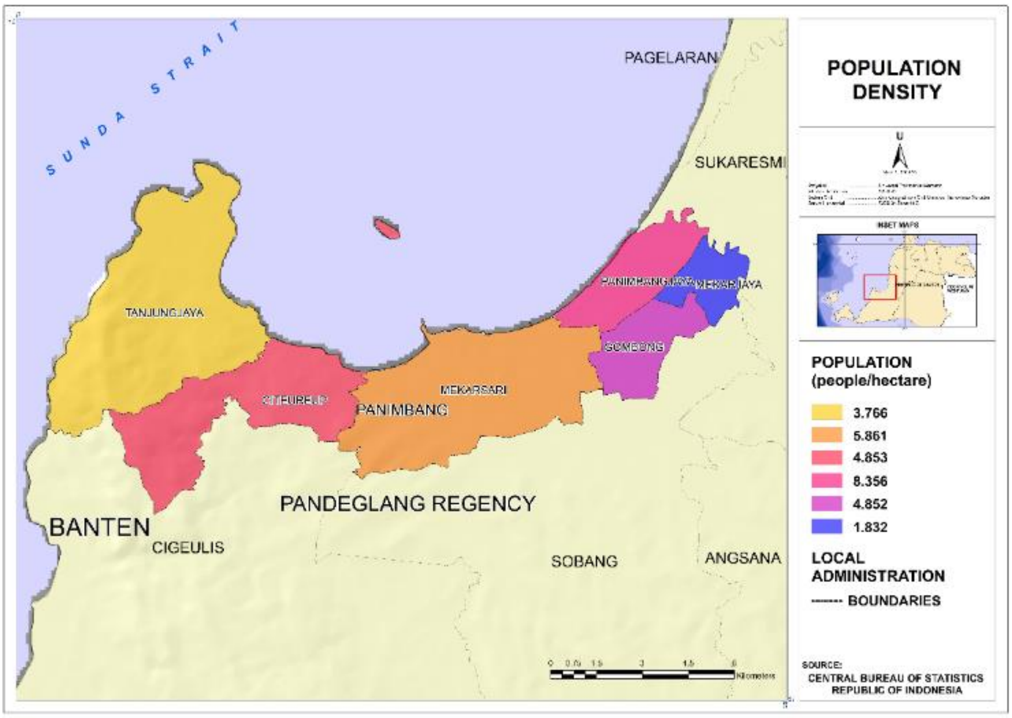

Figure 8. Population Density in Panimbang sub-district

Total Population in the Tsunami-Exposed Area

Figure 8 illustrates the population density in the Panimbang sub-district, which is a pivotal factor in assessing the potential human impact of a tsunami. The figure shows that areas such as Panimbang Jaya, Mekarsari, and Citereup have the highest population densities, corresponding to the regions with the most significant exposure to tsunami risks. This correlation emphasizes the need for focused evacuation strategies in these densely populated areas. The figure also highlights less populated areas, which, while still at risk, may require different evacuation strategies due to the lower concentration of people. The population exposed to the tsunami as a whole is known to be 384,089 or equivalent to 74.91% of the total population of the Panimbang sub-district with a total area of 512,734 Ha (fig.9). This amount was obtained based on the processing of the tsunami-exposed areas and the distribution of population density in the Panimbang sub-district.

Time of Evacuation when a Tsunami occurs

The maximum arrival time for a tsunami to the shoreline in Pandeglang Regency, according to (BNPB, 2012), is 25 minutes. However, it should be emphasized that this time applies to a tsunami height of 10 meters. The results of processing the evacuation time in the Panimbang sub-district found that the required evacuation time is more than 25 minutes, to be precise, a minimum of 32 minutes. These findings indicate that if the time needed for the wave to touch the shoreline is 25 minutes, then within 32 minutes of evacuation time, not all refugees will be in areas unaffected by the tsunami. It is known that the time required for residents of the Panimbang sub-district to evacuate to a safe area was at least 32 minutes and a maximum of 324 minutes, as illustrated in the figure. 9. The period for evacuation in the western and central regions, then along the edge of the sub-district administrative boundary to the southeast, was known to be longer due to land cover conditions that slow down human movement. The land cover was known based on the Speed Conservation Value (SCV) index. (Wood et al, 2012; Oliveira, 2020; Alvarez et al, 2018).

The cost distance calculation was used to predict the evacuation time. The calculation converted slope and land cover variables to speed conservation values. The SCV in land cover differed from the land cover index used to estimate the tsunami inundation area, even though the SCV was obtained from the same data. The differences were found in the resistance values given (Berryman, 2006). Regarding the movement of water masses, the smoother the surface and the larger the watershed or water reservoir, the lower the resistance value due to the difference in the SCV. Related to this, the existing value is based on how humans move places and what is likely to slow it down, namely the value of slope and land cover (Wood et al., 2012; Oliveira, 2020).

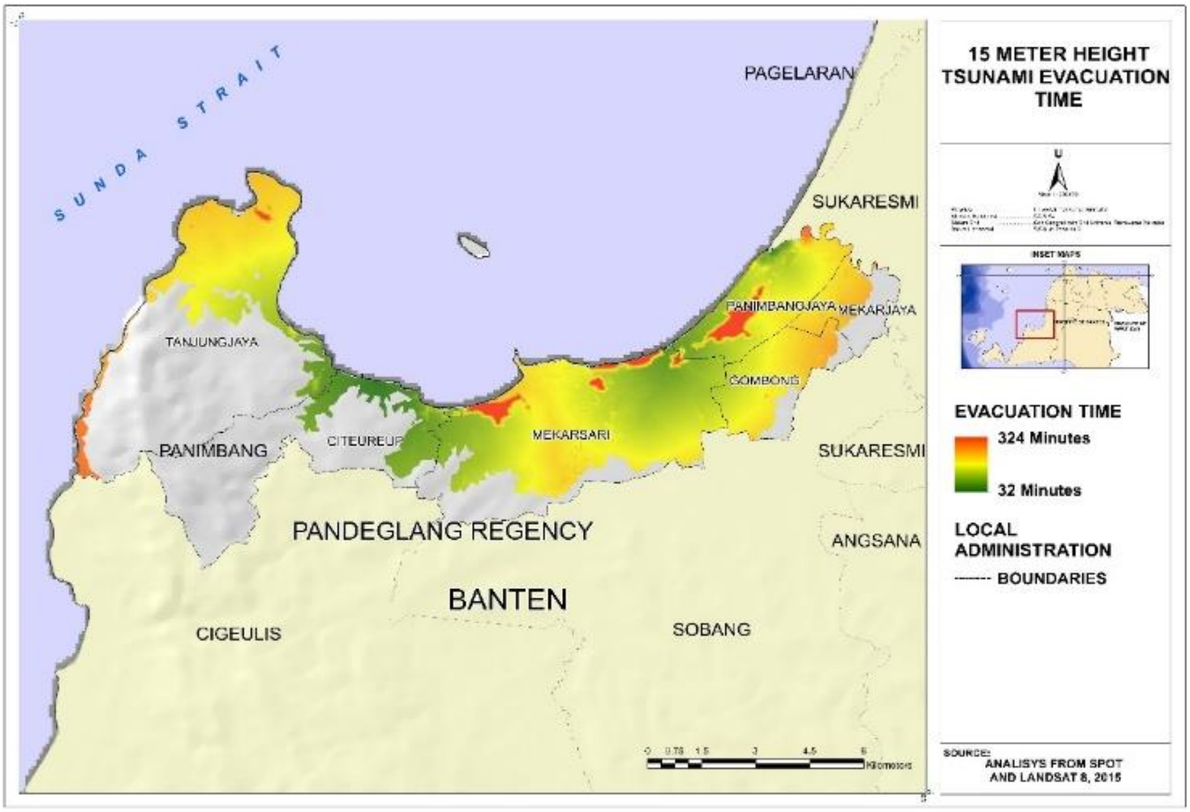

Figure 9. Tsunami Evacuation Time at height of 15 Meters in the Panimbang sub-district

The difference in evacuation time was found to be faster in areas around the coastline compared to areas located further from the coast. This happened in several areas, such as Mekarsari Village, Gombong Village, and Panimbang Jaya Village. The difference in evacuation time is indicated by the SCV classification of land cover, which is known to inhibit human movement in areas further from the coast than in areas near the coast (Leon et al, 2020) even though the slope in this case is flat.

Displacement of Refugees per Unit of Time

The number of residents who evacuated was found based on the results of processing the evacuation time data. In this case, the evacuation time was obtained from the results of data grouping (Figure 9.) The evacuation time estimates depicted in Figure 9 are particularly telling in terms of the region’s preparedness for a tsunami. The figure shows a gradient of evacuation times across the sub-district, with darker shades indicating areas that require longer evacuation periods. These longer times are primarily in regions with challenging topography and complex land cover, as shown in Figures 5 and 6. The relationship between land cover, topography, and evacuation time highlighted in this figure underscores the importance of improving evacuation infrastructure in specific areas to reduce the risk to residents. Subsequent cutting and grouping of settlements and population activity centers was carried out so that the classified data was based on the evacuation time. The classification of the evacuation time obtained in this research is as shown in Figure 10.

Figure 10 depicts the total number of refugees by evacuation time, further breaking down the population's evacuation dynamics. The classification of evacuation times into five distinct classes provides a clear understanding of how quickly different segments of the population can reach safety. The figure highlights that the majority of the population will need significantly more time than the estimated tsunami arrival time, which is a critical finding that calls for urgent improvements in evacuation planning and infrastructure. The evacuation time based on the picture above is classified into five classes (figure 10), which are 32 minutes, 64 minutes, 97 minutes, 129 minutes, and 162 minutes. The number of residents who evacuated was known based on the results of the evacuation time processing distribution of population density in tsunami-exposed areas. The number of residents who evacuated from the exposed zone to the safe zone at the 32nd minute is 5,823. In the next minute or 64th minute, 17,304 residents can evacuate. In the 97th minute, it is known that 13,689 residents can evacuate. Furthermore, the 4th or 129th-minute classification shows that 1,884 residents can evacuate to the safe zone. In the the last one, or at the 162nd minute, 23 residents evacuated.

Ultimately, the evacuation time calculation model must be further developed in further research. This is because the best evacuation route required needs to be determined further since there are no official evacuation routes and gathering points from the local government where this research is conducted.

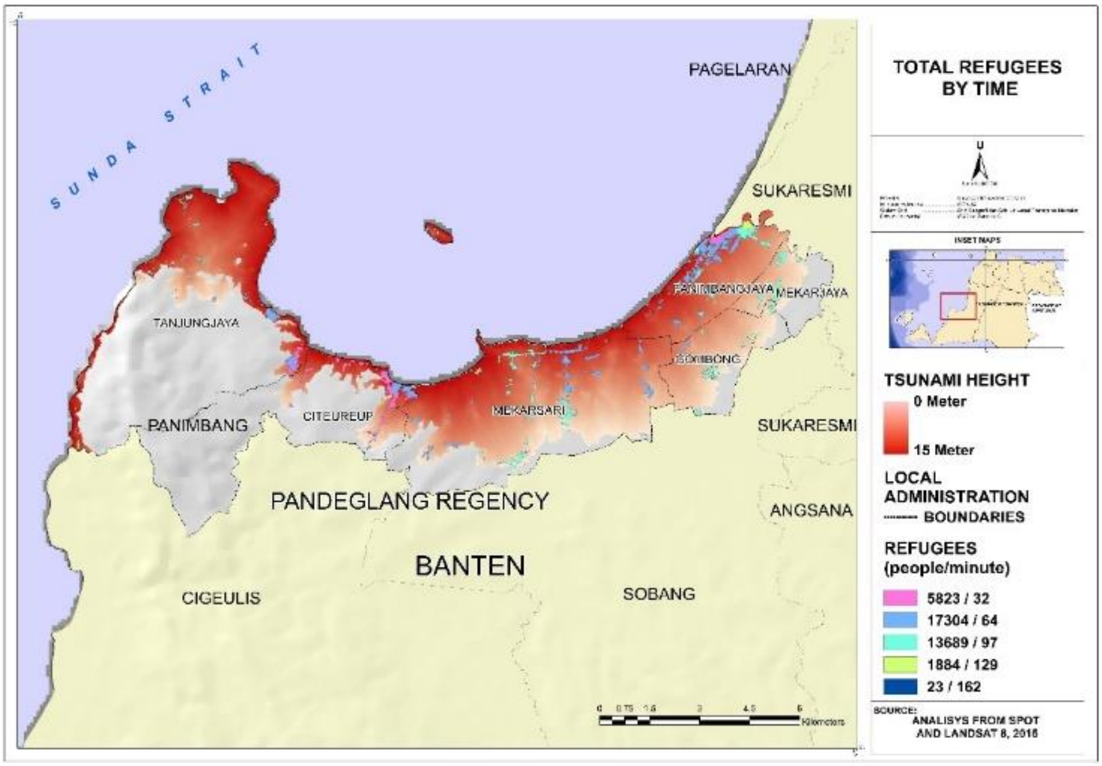

Figure 10. Total Refugees by Time in Panimbang Sub Disctrict

Conclusions

This study has comprehensively assessed the tsunami risk in the Panimbang sub-district, focusing on the region's evacuation capacity and the potential impacts of a tsunami event. The most significant outcome of this work is the identification of the high level of exposure, with 74.91% of the residential area and approximately 38,723 people at substantial risk. This finding underscores the critical need for tailored evacuation strategies specifically designed to address the region's unique geographical and demographic characteristics.

This study successfully addressed the need for a detailed analysis of evacuation capacity, demonstrating that the current infrastructure and preparedness levels are insufficient to ensure the population's safety. The findings highlight that evacuation times in many areas exceed the estimated time for a tsunami to reach the shore. This indicates a pressing need for improvements in evacuation routes and public awareness programs.

These results emphasize the importance of proactive disaster risk management for the community and readers. To increase the coping capacity of the population, it is essential to invest in enhanced evacuation infrastructure, such as the construction of more accessible and marked evacuation routes and the development of vertical evacuation shelters in high-risk zones. Additionally, community-based education and preparedness programs should be strengthened to ensure that residents are aware of the risks and know how to respond effectively in the event of a tsunami. Future research should explore integrating real-time monitoring systems with evacuation modeling to improve response times and effectiveness. By continuing to develop and refine these strategies, it is possible to significantly reduce the risk to human life and improve the overall resilience to tsunami hazards.

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Author contribution

Lestari DELLA AYU, Coordinator & person in charge of all research and publication processes and activities, theoretical and literature review, review of research instruments, data processing, data analysis and journal preparation.

Fitriasari NOVI SOFIA, Development of research design and operationalization in the field of coastal management.

Rais AMIEN, Collection and processing of predictive data on the development of built-up area.

Ahmad TAUFIQ EJAZ, Collection and processing of tsunami inundation data.

Azhari DHEA RAHMA, Collection and processing of population growth data.

Conflicts of interest

The authors declare no conflict of interest.

References

Almeida, S., Holcombe, E. A., Pianosi, F., & Wagener, T. (2017). Dealing with deep uncertainties in landslide modelling for disaster risk reduction under climate change. *Natural Hazards and Earth System Sciences*, *17*(2), 225-241.
https://doi.org/10.5194/nhess-17-225-2017

Arabameri, A., Pradhan, B., Rezaei, K., Yamani, M., Pourghasemi, H. R., & Lombardo, L. (2018). Spatial modelling of gully erosion using evidential belief function, logistic regression, and a new ensemble of evidential belief function–logistic regression algorithm. *Land Degradation & Development*, *29*(11), 4035-4049. https://doi.org/10.1002/ldr.3151

Ali, S. A., Khatun, R., Ahmad, A., & Ahmad, S. N. (2020). Assessment of cyclone vulnerability, hazard evaluation and mitigation capacity for analyzing cyclone risk using GIS technique: A study on Sundarban biosphere reserve, India. *Earth Systems and Environment*, *4*(1), 71-92. https://doi.org/10.1007/s41748-019-00140-x

Álvarez, G., Quiroz, M., León, J., & Cienfuegos, R. (2018). Identification and classification of urban micro-vulnerabilities in tsunami evacuation routes for the city of Iquique, Chile. *Natural Hazards and Earth System Sciences*, *18*(7), 2027-2039. https://doi.org/10.5194/nhess-18-2027-2018

Badan Nasional Penanggulangan Bencana, "Data Disaster Information Indonesia (DIBI)," November 2018,

Badan Nasional Penanggulangan Bencana, Regulation of the Head of the National Disaster Management Agency Number 02 of 2012 concerning General Guidelines for Disaster Risk Assessment.

Berryman, K. (2006). Review of Tsunami hazard and risk in New Zealand, report by the Institute of Geological and Nuclear Sciences. *New Zealand*. https://www.hbemergency.govt.nz/assets/Documents/Hazard-Reference-Documents/review-of-tsunami-hazard-and-risks-in-nz-sept-05.pdf

Besançon, L., Cooper, M., Ynnerman, A., & Vernier, F. (2020). An evaluation of visualization methods for population statistics based on choropleth maps. *arXiv preprint arXiv:2005.00324*. https://doi.org/10.48550/arXiv.2005.00324

Farahdita, W. L., & Siagian, H. S. R. (2020). Analysis of the area affected by the tsunami in Pandeglang, Banten: a case study of the Sunda Strait Tsunami. In *IOP Conference Series: Earth and Environmental Science* (Vol. 429, No. 1, p. 012052). IOP Publishing. https://doi.org/ 10.1088/1755-1315/429/1/012052

Faucher, J. E., Dávila, S., & Hernández-Cruz, X. (2020). Modeling pedestrian evacuation for near-field tsunamis fusing ALCD and agent-based approaches: a case study of Rincón, PR. *International journal of disaster risk reduction*, *49*, 101606.
https://doi.org/10.1016/j.ijdrr.2020.101606

Grilli, S. T., Tappin, D. R., Carey, S., Watt, S. F. L., Ward, S. N., Grilli, A. R. E., & SL, Z. C., Kirby, JT, Schambach, L. and Muin, M.(2019): Modelling of the tsunami from the December 22, 2018 lateral collapse of Anak Krakatau volcano in the Sunda Straits, Indonesia. *Scientific Reports*, *9*, 11946. https://doi.org/10.1038/s41598-019-48327-6

Hermon, D. (2019). Evaluation of physical development of the coastal tourism regions on tsunami potentially zones in Pariaman City-Indonesia. *GEOMATE Journal*, *17*(59), 189-196. 6 https://doi.org/10.21660/2019.59.66719

Horspool, N., Pranantyo, I., Griffin, J., Latief, H., Natawidjaja, D. H., Kongko, W., ... & Thio, H. K. (2014). A probabilistic tsunami hazard assessment for Indonesia. *Natural Hazards and Earth System Sciences*, *14*(11), 3105-3122.
https://doi.org/10.5194/nhess-14-3105-2014

Khomarudin, M. R., Strunz, G., Ludwig, R., Zoßeder, K., Post, J., Kongko, W., & Pranowo, W. S. (2010). Hazard analysis and estimation of people exposure as contribution to tsunami risk assessment in the west coast of Sumatra, the south coast of Java and Bali. *Zeitscrift*

fuer Geomorphologie, Supplementary Issues, *54*(3), 337-356.
https://doi.org/10.1127/0372-8854/2010/0054S3-0031

Khomarudin, M. R., Strunz, G., Post, J., Zobeder, K., & Ludwig, R. (2010). Derivation of population distribution by combining census and landuse data: As an input for tsunami risk and vulnerability assessment. *International Journal of Remote Sensing and Earth Sciences (IJReSES)*, *6*(1).
http://dx.doi.org/10.30536/j.ijreses.2009.v6.a1238

Kontar, Y., Santiago-Fandino, V., & Takahashi, T. (2016). *TSUNAMI EVENTS AND LESSONS LEARNED*. Springer. https://doi.org/10.1007/978-94-007-7269-4

León, J., Castro, S., Mokrani, C., & Gubler, A. (2020). Tsunami evacuation analysis in the urban built environment: A multi-scale perspective through two modeling approaches in Viña del Mar, Chile. *Coastal Engineering Journal*, *62*(3), 389-404. https://doi.org/10.1080/21664250.2020.1738073

Majid, R. N., & Nurlambang, T. (2020). Pandeglang regency spatial evaluation based on tsunami hazard potential. In *E3S Web of Conferences* (Vol. 156, p. 04010). EDP Sciences. https://doi.org/10.1051/e3sconf/202015604010

Oliveira, S., Gonçalves, A., Benali, A., Sá, A., Zêzere, J. L., & Pereira, J. M. (2020). Assessing risk and prioritizing safety interventions in human settlements affected by large wildfires. *Forests*, *11*(8), 859.
https://doi.org/10.3390/f11080859

Purnamasari, A. M. (2017). *Towards population density retrieval using gas-flare corrected DMSP-OLS night-time light observations* (Master's thesis, University of Twente).

Perka BNPB No. 2/2012 on General Guidelines for Disaster Resilient Villages.

Petrov, Y., Istomin, E., Stepanov, S., Sidorenko, A., & Vagizov, M. (2020, October). Development of a conceptual GIS model to support management decision making. In *IOP Conference Series: Earth and Environmental Science* (Vol. 574, No. 1, p. 012062). IOP Publishing.
https://doi.org/0.1088/1755-1315/574/1/012062

Pranantyo, I. R., & Cummins, P. R. (2020). The 1674 Ambon tsunami: Extreme run-up caused by an earthquake-triggered landslide. *Pure and Applied Geophysics*, *177*(3),
1639-1657. https://doi.org/10.1007/s00024-019-02390-2

Ramadan, K. T. (2018). Near-and far-field tsunami waves, displaced water volume, potential energy and velocity flow rates by a stochastic submarine earthquake source model. *Natural Hazards and Earth System Sciences Discussions*, 1-28.
https://doi.org/10.5194/nhess-2018-107

Romano, A., Lara, J. L., Barajas, G., Di Paolo, B., Bellotti, G., Di Risio, M., ... & De Girolamo, P. (2020). Tsunamis generated by submerged landslides: numerical analysis of the near-field wave characteristics. *Journal of Geophysical Research: Oceans*, *125*(7), e2020JC016157.
https://doi.org/10.1029/2020JC016157

Ren, Z., Wang, Y., Wang, P., Hou, J., Gao, Y., & Zhao, L. (2020). Numerical study of the triggering mechanism of the 2018 Anak Krakatau tsunami: eruption or collapsed landslide?. *Natural Hazards*, *102*(1), https://doi.org/1-13. 10.1007/s11069-020-03907-y

Sambah, A. B., Miura, F., & Febriana, A. F. (2019). Geospatial Model of Physical and Social Vulnerability for Tsunami Risk Analysis. *GEOMATE Journal*, *17*(63), 29-34. : https://doi.org/10.21660/2019.63.4684

Syahputra, B., Sujarwo, A., & Maharika, I. (2019, February). Bank Air Kami: Terban waterscape information system. In *IOP Conference Series: Materials Science and Engineering* (Vol. 482, No. 1, p. 012047). IOP Publishing.
https://doi.org/10.1088/1757-899X/482/1/012047

Suppasri, A., Leelawat, N., Latcharote, P., Roeber, V., Yamashita, K., Hayashi, A., ... & Imamura, F. (2017). The 2016 Fukushima earthquake and tsunami: Local tsunami behavior and recommendations for tsunami disaster risk reduction. *International Journal of Disaster Risk Reduction*, *21*, 323-330. https://doi.org/10.1016/j.ijdrr.2016.12.016

Widiyantoro, S., Gunawan, E., Muhari, A., Rawlinson, N., Mori, J., Hanifa, N. R., ... & Putra, H. E. (2020). Implications for megathrust earthquakes and tsunamis from seismic gaps south of Java Indonesia. *Scientific reports*, *10*(1), 1-11.
https://doi.org/10.1038/s41598-020-72142-z

Wang, Y., Satake, K., Sandanbata, O., Maeda, T., & Su, H. (2019). Tsunami data assimilation of cabled ocean bottom pressure records for the 2015 Torishima volcanic tsunami earthquake. *Journal of Geophysical Research: Solid Earth*, *124*(10), 10413-10422. https://doi.org/10.1029/2019JB018056

Wood, N. J., & Schmidtlein, M. C. (2012). Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest. *Natural Hazards*, *62*(2), 275-300. https://doi.org/10.1007/s11069-011-9994-2

Widyaningrum, E. L. Y. T. A. (2009). Tsunami Evacuation Planning Using Geoinformation Technology Considering Land Management Aspects. *Case Study: Cilacap, Central of Java, Centre of Land and Environmental Risk Management, Technische Universität München, Munich, Germany*.
https://doi.org/10.13140/RG.2.2.31656.98567

Yulianto, F., Tjahjono, B., & Anwar, S. (2014). Detection settlements and population distribution using GIS and remotely sensed data, in the surrounding area of Merapi Volcano, Central Java, Indonesia. *Int. J. Emerg. Technol. Adv. Eng.*, *4*(3), 1-10.