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Environmental perspective on tsunami disaster mitigation and its implications: a critical review

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Abstract
Tsunamis are one of the deadliest and most destructive natural disasters, having the potential to cause significant damage to the environment and society. Therefore, tsunami hazard modeling becomes very important in disaster risk management and environmental protection. Tsunami evacuation isan important and effective effort that must be carried out to save the community when a tsunami occurs. The aim of this study is to review the environmental perspective on the tsunami evacuation plan in terms of environmental, social, and economic aspects, along with their implications. Aqualitativedescriptive study was carried out through a literature review by comparing case studies in various coastal areas affected by the tsunami. Environmental factors play an important role in the results of tsunami modeling which will form the basis for evacuation plans.Social and economic aspects also play a role in people's behavior when evacuating, reviewed and observed, in order to produce an effective and sustainable evacuation plan.

Keywords: environmental; economic; evacuation; social; sustainable tsunami modeling

1. Introduction

A tsunami is a sea wave that arises due to a sudden disturbance on the seabed. Although there are various causes of tsunamis, tectonic earthquakes are the most common cause. The size of a tsunami is influenced by earthquake parameters, but not all earthquake events at sea have the potential for a tsunami.

Studies focused on quantitative assessments of the vulnerability of peoplewith the key factors describing them during the 2004 Aceh Tsunami were conducted by Koshimura *et al.* (2009). This study uses regression analysis to develop afunction of fragility, based on the human mortality ratio derived fromselecteddata tsunami modeling and recorded statistics on the aftermath of the tsunami. This function uses the recorded number of death, disappeared, and survivingvictims in 88 villages plus the tsunami depth model.

To formulate a scenario-based logistic regression (CR) model, Yun and Hamada (2015) interviewed with 1,153 witnesses and used data on the behavior of victims and the number of unaccounted-for fatalities related to the 2011 Tohoku Earthquake. The model was created with the goal of identifying variables that might have affected life safety during the tsunami catastrophe. They discovered that the tsunami's height, the population's age, its velocity, and the environment in the analysis region all had a significant impact on the number of casualties.

Suppasri *et al.* (2016) examined fatality ratios and the variables impacting human mortality during the same recorded event using precise data from a geographical region of less than 3 km2 (inundation ratio larger than 70%). Their research revealed that human, geographical, and tsunami features all have an impact on the fatality ratio.

A human vulnerability index (HVI), calculated from the mortality rate and incidence rate of structures impacted by the tsunami, was proposed by Goto and Nakasu (2018) using observed data from the 2011 Tohoku Earthquake. They also used multivariate regression analysis to isolate four explanatory variables for the aforementioned index: (1) setback period (time of tsunami arrival divided by the distance to safety), (2) preparedness, (3) road serviceability, and (4) effect of the warning (combined from the multiplication of the announced tsunami height and warning cognition level).

Latcharote *et al.* (2018) examined the results for the two topographically diverse coastal locations while also integrating the fatality ratios based on the survey with the tsunami's arrival time to assess the association between the two factors. They came to the conclusion that the death ratio reduced as the tsunami's time of arrival grew and that, in the instance of the Sendai Plain, women and the elderly who met the age requirement of over 65 years had greater fatality rates than the category of males. Yavuz *et al.* (2020) assessed social, economic, and environmental threats on the eastern Mediterranean coast using probabilistic tsunami modelling. The amount of individuals who live in places with an inundation depth of at least 0.5 metres is specifically defined as social risk. This study also focuses on the most essential geographical and environmental factors contributing to the effectiveness of a tsunami evacuation, even if the socio-psychological element is a significant driver of evacuation. Determine the function of environmental, social, and economic factors and their consequences for disaster risk reduction is the goal of this critical review research.

2. Methods

Through a literature review, a descriptive qualitative methodology was used for the methodology. According to Sukmadinata (2019), qualitative descriptive research focuses more on qualities, quality, and connections between activities to describe and describe current occurrences, both natural and man-made. To assess the significance of environmental elements in tsunami hazard modelling and their implications for catastrophe risk reduction, case studies from different cities throughout the world were compared.

The first stage is planning which consists of problem identification and preparation of a review protocol (Palmon & Robindson, 2009). Problem identification was carried out in various case studies to find its implementation in various cities in the world and search for literature that discusses how environmental factors influence the results of tsunami modeling simulations in affected coastal areas. A literature review protocol needs to be developed to address this problem by finding one main article to be reviewed with the most recent and high-impact criteria. The second stage is an article review by searching for main articles, supporting articles, and main article reviews (Palmatier *et al.*, 2018). The main article search is carried out by selecting the most recent and quality articles that have gone through a review process by experts (peer-reviewed). The process of searching for articles is carried out by checking by evaluating articles that are relevant to the topic and purpose of the review starting from the title of the article, abstract, and keywords (tsunami modeling, environmental factors, risk reduction, and disaster management). The main article search is carried out by limiting the year of publications and eventually, several articles were obtained in the period 2021 to 2023.

The article selection process is carried out by evaluating articles that are relevant to the topic and purpose of the review. Right after the articles were sorted from the most recent year, two articles were selected by León et al. (2022) entitled “Modeling Geographical and Built-environment Attributes as Predictors of Human Vulnerability During Tsunami Evacuations: A Multi-case-study and Paths to Improvement” and Takabatake et al. (2022) entitled “Simulated Effectiveness Of Coastal Forests On Reduction In Loss Of Lives From A Tsunami”. Search for supporting articles by searching for other scientific articles as secondary sources to support the arguments or findings in the main article. Supporting articles are selected based on their relevance and quality in the same field as the main article, and are used to provide a broader understanding of the topics discussed.

The 3rd stage is literature analysis by analyzing the selected literature to identify environmental factors that influence tsunami hazard modeling and their implications for disaster risk management (Koh *et al.*, 2018). Literature synthesis was carried out to compile a comprehensive review of the role of environmental factors in tsunami hazard modeling and their implications for disaster risk management. Journal writing is carried out with a systematic and coherent structure, including an introduction, literature review, analysis and synthesis, conclusions, and suggestions for further research. Using this method, it is possible to develop a comprehensive review of the role of environmental factors in tsunami hazard modeling and their implications for disaster risk management.

3. Results and Discussion

Tsunamis are one of the deadliest natural disasters and damage the environment (Imamura *et al.*, 2019). Environmental factors, such as topography, bathymetry, vegetation, and seasurface conditions, can affect the intensity of a tsunami and its impact on society and the environment (Selvakumar & Ramasamy, 2012). Therefore, understanding and modeling environmental factors is key to understanding the tsunami hazard and minimizing its impact. Figure 1 is an example of the impact of the Sunda Strait tsunami on December 22 of 2018 (Solihuddin *et al.*, 2020).Therefore, for disaster mitigation purposes, tsunami hazard modeling is important in risk management, environmental protection, and evacuation planning.

Figure 1. A densely populated residential area in Kertajaya Village, Sumur, Pandeglang, Banten which was destroyed by the tsunami on December 22, 2018.

Evacuation is the most crucial and efficient way to save lives during a tsunami, claim León *et al.* (2022). Some geographical and environmental factors that affect the effectiveness of the evacuation process may be statistically assessed (via regression analysis) using inundation, evacuation, and metrics modelling techniques to the layout of coastal communities in Chile. This study is a type of comprehensive, cutting-edge research that uses modelling, evacuation tools, and very new multivariate statistical techniques. Even if there is still much to be done in this type of research, it can be concluded that geography and environmental factors have a significant impact on whether the evacuation procedure is successful or unsuccessful when a tsunami hits (Figure 2).

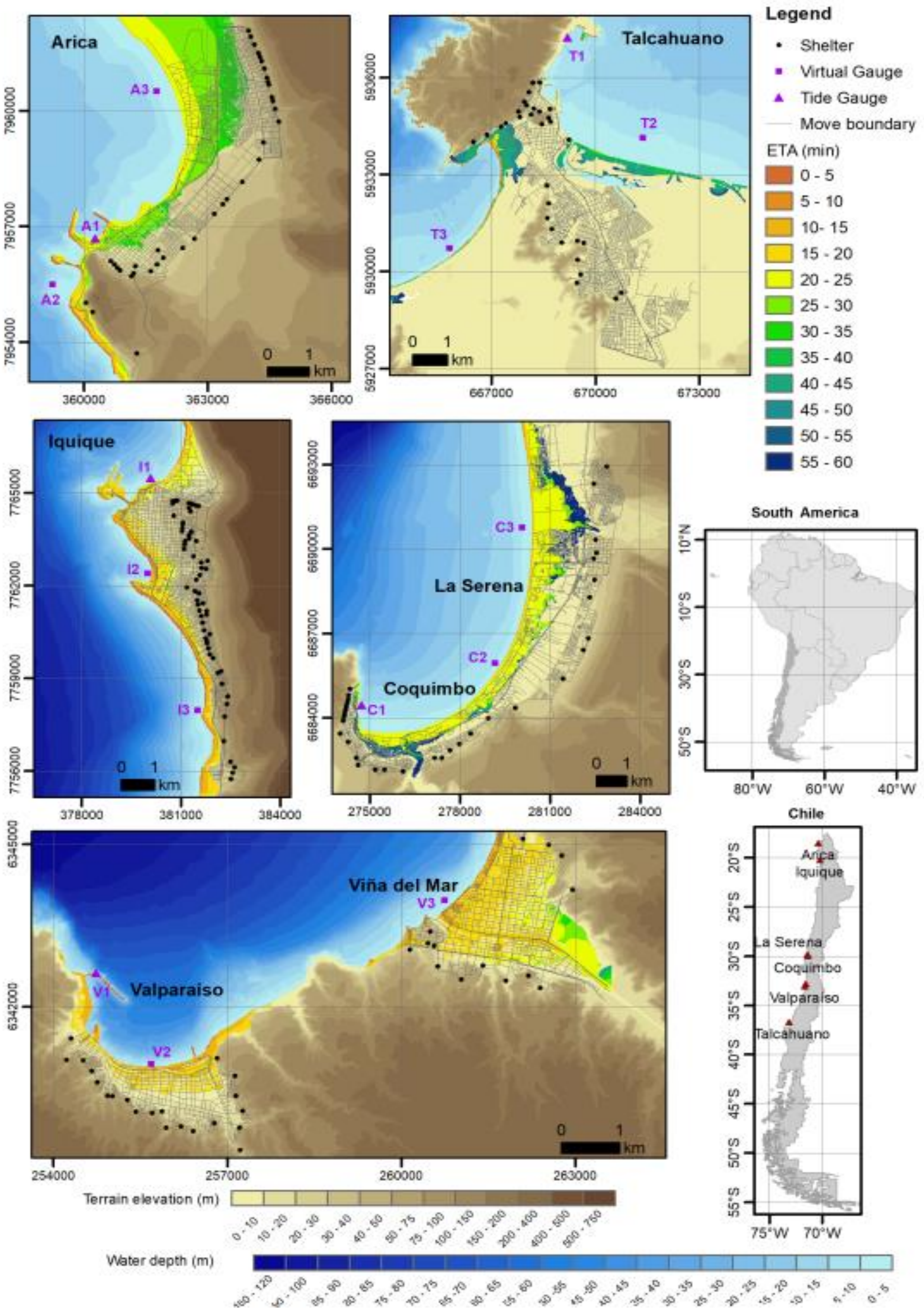

Figure2. From a case researched in Chile, location, topography, bathymetry, and tsunami-related characteristics were examined (León *et al*., 2022).

Some cities that have about 55% of movement limit between the coastline and the temporary evacuation site are vulnerable to casualties or death for people who are doing evacuation. This study is able to assess or assess coastal areas and provide an overview of the coastal city space and recommend a broader and wider city condition to secure and facilitate the tsunami evacuation process. In this case, it is very suitable for coastal urban planning that has not been developed and is well established. The results of this study are very important to be used as a reference basis in planning a tsunami risk-based coastal city area that is more spacious, not narrow and congested, with wide straight roads away from the coast. Coastal spatial planning based on tsunami risk is very important to realize (Putra, 2011).

For the current era, changing an established city to be more spacious is not an easy thing. So in this context, this recommendation is considered unrealistic, because it is quite difficult to realize, even though the goal is very useful and important to save coastal communities. Why not think about vertical evacuation options that are more likely to be realized in established cities with dense populations?. Geographical variables, the shape of the city, the evacuation route, the maximum tsunami inundation height, the straightness of the route, the length of the evacuation route, and the average travel time have a significant impact on the death ratio (Reis et al., 2022; McLaren, 2021). The average city shape metric is also related to the refugee mortality ratio threshold.

This study seems to only focus on the concept of horizontal evacuation which does not consider vertical evacuation options at all. Vertical evacuation isactually more accommodating for an established city. At present, vertical evacuation has become an option in line with the development of engineering technology for earthquake and tsunami-resistant buildings. Vertical evacuation is not risky with the short tsunami arrival time. The success of this vertical evacuation was proven when the 2011 Sendai tsunami hit Sendai Airport, where thousands of people survived just by holding on to the airport's tall buildings (Hradecky, 2011).

Even though there is no artificial tsunami barrier to control tsunamis yet, urban form metrics such as the straightness of the road network can be improved, to speed up the travel time of people who evacuate. The recommendation on the importance of "redesigning" urban planning is one of the results of the study, this gives weight to the research results which provide great benefits. If there are no tsunami barrier structural buildings, efforts can be made to improve the route by maximizing the alignment of the road network, to speed up the evacuation time (Ismantohadi & Iryanto, 2018).

Takabatake *et al.* (2022) conducted a study aimed at investigating the effectiveness of coastal forests in reducing tsunami-related casualties using propagation and inundation simulation models adapted to evaluate vegetation-induced resistance (Figure 3). This model was used to simulate the inundation observed on Shobutahama Beach in Miyagi Prefecture, Japan, during the 2011 Tohoku Tsunami, then applied to consider various layouts of countermeasures (e.g., coastal embankments and evacuation signs) and the presence or absence of coastal forests. Even in the simulations that only considered the coastal forest, the simulated casualty rate was reduced by a maximum of about 54%, compared to cases where no countermeasures were implemented.This reduction was due to a delay in the arrival time of the tsunami due to vegetation-induced resistance, thus confirming the effectiveness of the coastal forest in reducing the number of victims.

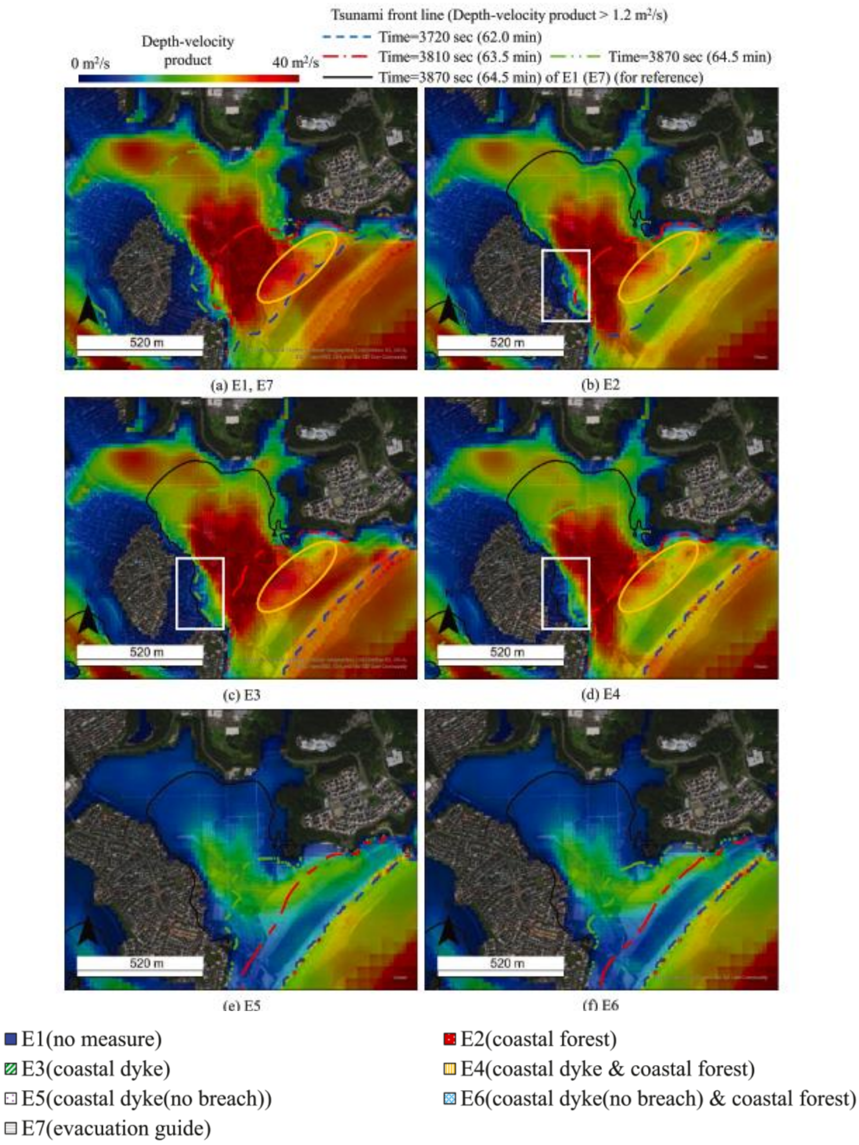

Figure 3. Spatial distribution of simulated inundation depths for each evacuation scenario and time history of inundation depth at Point A and Point B (Satellite imagery sources: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and Community GIS users). (Takabatake *et al*., 2022)

When simulating the presence of a coastal embankment that could withstand tsunami inundation, a more significant reduction in the casualty rate was obtained (approx. 97% maximum). Therefore, to significantly reduce casualty rates, increasing the resilience of coastal structures may prove more beneficial than planting new coastal forests (at least in the study area). Implementing a combination of coastal forests and dikes has proven to be more effective than considering either approach separately (Nateghi *et al*., 2016). Therefore, to minimize the number of casualties from a significant tsunami event, it is recommended that coastal forests be used together with tsunami-resistant coastal structures. Inevitably, the effectiveness of coastal forests and other mitigation will vary depending on the study area and the characteristics of the incident waves (Yudhicara, 2016). Therefore, it is important to apply the developed model to different coastal cities while considering different possible tsunami waves in order to better determine the effect that a coastal forest can have on the expected number of victims.

In the view of modern mitigation, it seems that building a "*tsunami barrier*" is not the right choice, because constructive environmental issues are not in line with the concept of building a tsunami barrier (Susanto *et al*., 2018). When the 2011 Sendai tsunami was able to submerge this tsunami barrier, the impact was actually very deadly because the tsunami run-off could not flow back into the sea but instead created inundation pads that submerged coastal areas. Until now, the mitigation system with a structural building such as a tsunami barrier is still being debated by experts and practitioners of disaster mitigation.

The need to incorporate social aspects of the community in modeling tsunami hazard and tsunami evacuation to ensure successful evacuation and reduce the social impact of the tsunami disaster. In tsunami modeling, considering social factors such as population density, community social structure, and level of disaster awareness can help to estimate the level of community vulnerability and risk to tsunamis (Ibad & Santosa, 2014).

Meanwhile, in the evacuation process, considering social factors such as the special needs of the community, accessibility of evacuation sites, and the role of community leaders can help ensure that evacuation is carried out effectively and efficiently and takes into account the needs of the community. Incorporating the social aspects of tsunami modeling and evacuation processes can help increase understanding of the complexities of the tsunami disaster and increase the ability of communities and authorities to respond. This can help reduce the social impact of the tsunami disaster and accelerate community recovery after the disaster occurs (Variadi & Legono, 2012). Studying the social aspects of the evacuation process is very important because evacuation basically involves social interaction between individuals, groups, and society as a whole. Social aspects that need to be considered include the role of the family, social governance and coordination, the level of community participation in the evacuation process, and the handling of psychological problems that arise during and after evacuation.

In a disaster situation such as a tsunami, the role of the family is very important because the family is the smallest unit in society. Yunarto and Sari (2017) state that the arrival time of a tsunami in several vulnerable areas can vary, especially for islands that are very close to the earthquake source, the tsunami can come within a short time after the earthquake occurs. Therefore, people in coastal areas do not have enough time to wait for a tsunami early warning. It is indeed important to consider family relationships and understand how they affect the evacuation process. In addition, social governance and coordination are also important to consider as these can affect the effectiveness and efficiency of the evacuation process. The level of community participation in the evacuation process must also be considered, because the more community participation in the evacuation process, the more likely the evacuation will be successful.

Miyazaki (2022) found that there was a positive relationship between the height of the tsunami, population, the proportion of three-generation households, and the proportion of employees working in the manufacturing industry with the death rate from the tsunami. This finding is consistent with the results of previous studies which confirmed the relationship between the height of the 2011 Tohoku tsunami and mortality rates (Suppasri et al., 2013; Aldrich & Sawada, 2015; Latcharote *et al.*, 2018). This is because when the tsunami occurred, many people wanted to escape with their families. Therefore, people living in households of 3 generations take longer to reach a safe place with their families, and are more vulnerable to tsunamis. This finding is in line with previous research by Tanaka and Shimomura (2021) and Bauer et al., (2022) who found that people with a high proportion of 3-generation households are more vulnerable to disasters. In addition, employees in manufacturing industries tend to participate less in disaster risk reduction activities in their communities compared to children and the elderly, resulting in weak social cohesion in the community and failure of disaster risk awareness and preparedness. Therefore, the characteristics of work in the community is also an important factor in determining the death rate from the tsunami. Other findings show that the high impact of the tsunami, the proportion of three-generation households and employees in the manufacturing industry is greater among older adults. This shows that these variables are important factors for people who are vulnerable to the tsunami disaster.

Shapira *et al*. (2018) stated that people with low socioeconomic status are more vulnerable. Occupation and socioeconomic status have a significant influence on evacuation behavior, where occupations with high risk and low socioeconomic status tend to have lower levels of awareness and preparedness in dealing with the threat of a tsunami. For this reason, it is necessary to build resilient communities through awareness and preparedness strategies that will protect lives, livelihoods, and property from tsunamis through collaborative efforts to meet tsunami preparedness levels. Building a tsunami-resistant community is in line with the goal of sustainable development, namely making cities and human settlements inclusive, safe, resilient and sustainable (UNESCO, 2022).

As part of Indonesia's efforts to reduce disaster risk, the Meteorology, Climatology and Geophysics Agency (BMKG) supported by IOTIC UNESCO/IOC organized the Tsunami Ready program which is a Community Performance-Based Tsunami Recognition Program developed by the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO/IOC). The aim of the Tsunami Ready recognition program is to build resilient communities through awareness and preparedness strategies that will protect lives, livelihoods, and property from tsunamis. This program was achieved through collaborative efforts to meet the predetermined level of tsunami preparedness through the fulfillment of 12 predetermined indicators which were grouped into three categories, namely risk knowledge assessment, preparedness steps, and response planning. In 2022, the Tanjung Benoa Village in Bali, Indonesia, was recognized asTsunami Ready (UNESCO, 2022). This gives vulnerable coastal communities the power to take effective action against potential tsunamis and save lives. Actions taken included making inundation and evacuation maps specifically for the community, as well as installing signs indicating evacuation routes, assembly points, and tsunami hazard zones (Figure 4). In 2022, the Tanjung Benoa Village in Bali, Indonesia, will be recognized as Tsunami Ready (UNESCO, 2022). This gives vulnerable coastal communities the power to take effective action against potential tsunamis and save lives. Actions taken included making inundation and evacuation maps specifically for the community, as well as installing signs indicating evacuation routes, assembly points, and tsunami hazard zones (Figure 4).

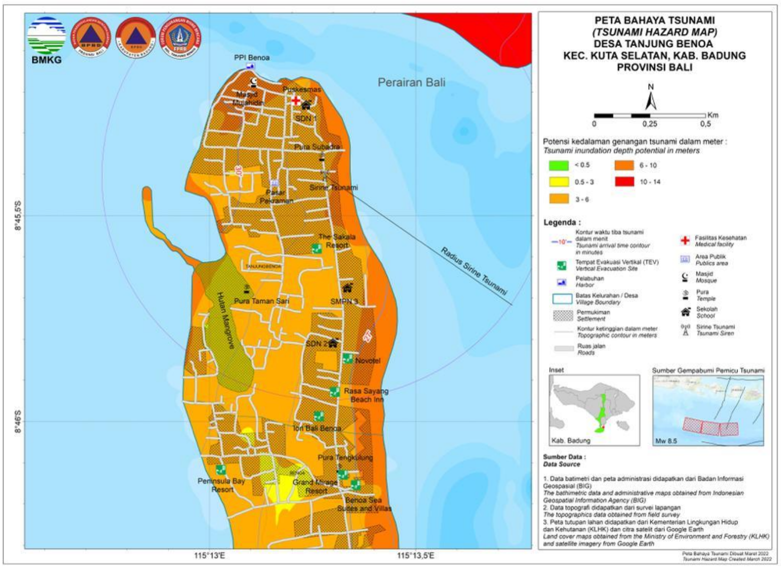

Figure 4. Tsunami hazard map of Tanjung Benoa Village, Bali. (UNESCO, 2022)

4. Conclusions

1. In terms of the environment, the evacuation plan must consider the topography of the area, distance from the coast, and accessibility to residential areas, to help determine the most effective and safe evacuation route.
2. The social aspect of the evacuation plan relates to population density, the presence of old people and children, the proportion of vulnerable people, the disabled, and the poor. A good evacuation plan takes into account the needs and limitations of the people in vulnerable areas.

3. The economic aspect is also important because an evacuation plan requires significant financial resources, helps prevent losses due to disasters, can allocate resources effectively and efficiently, and is able to guarantee security and safety to increase the attractiveness of investment in disaster-prone areas.
4. The implications of considering environmental, social and economic aspects in tsunami mitigation can produce effective and sustainable evacuation planning.

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