Area based tsunami risk assessment in West Aceh and Nagan Raya Regencies

H Q A’yun¹, V K Putri¹, W A Pramana¹, A Chrysanti², M B Adityawan³ and M Farid⁴

¹Undergraduate Student of Water Resources Engineering and Management, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Indonesia
²Water Resources Engineering Research Group, Institut Teknologi Bandung, Jalan Ganesha 10, Jawa Barat 40132, Indonesia
³Department of Water Resources Management and Engineering, Institut Teknologi Bandung, Jatinangor, Jawa Barat 45363, Indonesia
⁴Center for Coastal and Marine Development Institut Teknologi Bandung, Jalan Ganesha 10, Jawa Barat 40132, Indonesia

Corresponding author: hanaqu3@gmail.com

Abstract. West Aceh and Nagan Raya Regencies are traversed by the active Great Sumatran Fault, which makes the area vulnerable to geological disasters such as tsunamis. A great Indian Ocean tsunami struck Aceh in 2004. The tsunamis causing injuries, loss of life, and economic downturn as a result of the paralysis of the agricultural sector. Therefore, tsunami disaster mitigation efforts are highly needed in West Aceh and Nagan Raya Regencies. A risk assessment was carried out based on the Regulation of the Head of the National Disaster Management Agency No. 2 of 2012. This study modifies the risk index to provide a more proportional value, employing a simple yet more detailed method than the general method. HEC-RAS 5.0.7 software was used to determine the height of tsunami propagation in the scenario of an 9.1 Mw earthquake, which is based on a previous study. The assessment shows that the area is predominantly at high risk of tsunami. The area based method proved to be more detailed and appropriate than the previous risk index. Disaster mitigation plans are suggested according to both structural and non-structural approaches and are expected to reduce the risk of tsunami-related disasters in West Aceh and Nagan Raya Regencies.

1. Introduction

According to data released by the Central Statistics Agency, West Aceh and Nagan Raya Regencies cover a surface area of 2927.95 km² and 3544.9 km² respectively. Spread along the west coast, they have a flat topography of 0-2% [1]. The largest tsunami experienced by these two regions occurred in 2004 following an earthquake which had a magnitude 9.1 Mw [2]. The 2004 earthquake had a rupture length of approximately 1200 km [3] [4].
According to Regulation of the Head of the National Disaster Management Agency (BNPB) No. 8 of 2011 [5], a tsunami is a series of giant sea waves arising as a result of shifts in the seabed caused by earthquakes. These colossal sea waves can inflict harm upon the area they affect. Besides sudden hit of tsunami waves, the tsunami intrusion through river also bring significant impact in tsunami propagation [6]. The 2004 tsunami reached the mainland and severely damaged the coastal area of several regions [7]. The shoreline will severely damage and significantly changes due to the tsunami [7] [8]. The shoreline changes will disrupt the coastal balance and become a threat to coastal infrastructure [9].

The tsunami caused hundreds of thousands of people dead and missing, destroying thousands of homes, schools, office buildings and everything in front of the tsunami. In numbers, it caused the loss of 60,065 lives and damaged 21,412 houses in the city [10]. The earthquake and tsunami that hit the Aceh and other Indian Ocean regions on 2004 was recognized as the biggest natural disaster and the biggest damage to the Asian region, this is the fifth largest earthquake for a century [11]. Therefore, conducting a tsunami risk assessment is necessary to reduce the losses. Structural mitigation is recommended for coastal area with strong wave especially tsunami [9] [12]. However, the structure needs to consider the possibility of local scour behind the structure [13].

Disaster risk represents the potential harm caused by a disaster in an area over a certain period of time, in the form of death, injury, illness, threats to livelihoods, degradation of security, displacement, damage or loss of property, and disruption of community activities [14]. This study focuses on the transformation in West Aceh and Nagan Raya Regencies. In West Aceh and Nagan Raya Regencies, the tsunami caused injuries, loss of life, and an economic downturn, particularly in the agricultural sector.

Conducting a tsunami disaster risk assessment constitutes a form of disaster management. Such an assessment comprises three components, namely the appraisal of hazards, vulnerabilities, and capacities [15]. The Aceh Disaster Management Agency (BPBA) conducted a disaster risk assessment in 2015 [1], which characterized the levels of hazard, loss, and risk as high, while the level of capacity was considered medium. However, a deeper assessment of tsunami disaster risk is needed to prepare for future tsunamis. In this study, the present risk assessment was adapted from the General Guidelines for Disaster Risk Assessment set by Regulation of the Head of BNPB No. 2 of 2012 [14]. Several indexes were adjusted to take into account the ratio of affected area to study area. Land use in the affected area is also taken into consideration, and the study uses more recent data. Risk assessment maps were generated according to indexes evaluating each component, which were then combined into a comprehensive tsunami risk map.

Two-dimensional modeling of tsunami propagation was performed with HEC-RAS 5.0.7 software. The simulation of two-dimensional numerical model using shallow water equation has been commonly used in tsunami propagation [20]. HEC-RAS is commonly used for flood simulation. The software considered as the robust software to simulate the dam break flow which is similar to tsunami flow [17].

The purpose of this method was to provide a basis for the design of disaster management policies through risk assessment and mitigation plan [18]. This confirms that disaster management aims to reduce risk through structural and non-structural approaches [19]. The modified method of risk assessment using area based method are expected to provide a more proportional value, employing a simple yet more detailed method than the general method.
2. Methodology

In general, risk can be interpreted as the possibility that an event will cause material losses, environmental damage, or loss of life [20]. Risk is highly dependent on the interaction between the levels of hazard, vulnerability, and capacity. Awareness of an area’s risk level can form the basis for the implementation of a disaster management plan.

A deeper and more accurate study of tsunami hazards is essential to deal with potential tsunami disasters on the coastal area of West Aceh and Nagan Raya Regencies. In addition, a vulnerability and capacity assessment should be conducted. Assessments according to each index were carried out at the sub-district level, as shown in Figure 1. Each index determines levels through the assignment of values: < 0.33 for low, 0.33–0.67 for medium, and > 0.67 for high.

This study modified the risk index from the Regulation of the Head of BNPB No.2 of 2012 to provide a more proportional value through the use of micro-zonation, a simple method which is more detailed than the general macro-zonation method. The micro-zonation method considers not only the maximum height of the tsunami but also the percentage of affected area, which corresponds to the ratio between the exposed area and the total area under study. This is important because the unaffected area can be utilized as an evacuation alternative. Therefore, the smaller the affected area, the more evacuation sites available and the higher the capacity. The vulnerability index was also adjusted to include land use in the affected area, producing more detailed results, as the calculation only concerned the affected area.

2.1. Tsunami hazard index

A hazard is an event that has the potential to cause accidents, injuries, loss of life or loss of property. It is considered a disaster if it causes casualties and losses. The tsunami hazard index results were obtained through micro-zonation, a method which uses the relationship between inundation depth and percentage of affected area, as shown in Table 1. The index sets three levels of tsunami hazard: low (L), medium (M), and high category (H).
Table 1. Hazard index

| Hazard Level       | Affected Areas |
|--------------------|----------------|
|                    | Low <20% | Medium 20-50% | High >50% |
| Hazard Index       |          |               |           |
| Low <1m            | L        | L             | M         |
| Medium 1-3 m       | L        | M             | H         |
| High >3m           | M        | H             | H         |

Tsunami hazard index build based on the Great Sumatera tsunami on December 26, 2004 with 9.1 Mw. Tsunami propagation from rupture source has been conducted in the previous study using three-dimensional hydrodynamic model 3DD [20]. The model has been validated using observed tide gauges during the great Sumatra tsunami on December 26, 2004. The fault scenario considered based on five fault segments from Tanioka et.al [21]. The tsunami elevation in several location nearshore on Aceh coast is obtained from the simulation using 3DD in previous study [20], then we continue to simulate the tsunami run up and inundation using HEC-RAS in our study area. We selected the tsunami elevation at Meulaboh for the boundary condition. The Shuttle Radar Topography Mission (SRTM) data from the Consortium for Spatial Information were used as the bathymetry and the topography data in the model. The model domain and initial tsunami water level is shown in Figure 2.
2.2. Tsunami vulnerability index

Vulnerability is a condition of a community or society that leads to or causes an inability to face a disaster hazard [1]. Vulnerability analysis can act as a reference to determine whether a hazard can cause a disaster. The tsunami vulnerability index was obtained by reviewing the parameters shown in Table 2.

| Table 2. Vulnerability index |
|-----------------------------|
| Component                  | Weight (%) |
| Social Conditions          | 40         |
| Physical Conditions        | 25         |
| Economic Conditions        | 25         |
| Environmental Conditions   | 10         |

Based on the results, a vulnerability map was prepared to show the condition of the region.

2.3. Tsunami capacity index

The capacity index addresses the level of local resilience at a given time. The level of regional resilience has the same value for the entire region in a regency or city, which is the lowest geographical scope of this capacity study [14].

2.4. Tsunami risk index and analysis

The tsunami risk index defines the potential negative impacts of a tsunami disaster in the region, which was calculated on the basis of the three components previously analyzed, namely the hazard index, vulnerability index, and capacity index. The relationship between the components is formulated as follows:

\[ R = \sqrt[3]{\text{Hazard} \times \text{Vulnerability} \times (1 - \text{Capacity})} \]  

In preparing a disaster risk study after obtaining the required index, there is a need for an additional device, which consists of the determination of the hazard level, vulnerability level and capacity level, and the determination of disaster risk level. There are three levels to each parameter, i.e., low (L), medium (M), and high (H).

| Table 3. Level of hazard |
|--------------------------|
| Hazard Level             | Exposed Population Index |
|                          | Low | Medium | High |
| Hazard Index             |     |
| Low                      | L   | L      | M    |
| Medium                   | L   | M      | H    |

| Table 4. Level of loss |
|------------------------|
| Losses Level           | Losses Index |
| Low                    | Low | Medium | High |
| Hazard Level           |     |
| Low                    | L   | L      | M    |
| Medium                 | L   | M      | H    |
| Hazard Level | Low   | Medium | High |
|--------------|-------|--------|------|
| Low          | M     | H      | H    |
| Medium       | L     | M      | H    |
| High         | L     | L      | M    |

**Table 5. Level of capacity**

| Disaster Risk Level | Losses Level | Capacity Level |
|---------------------|--------------|----------------|
| Low                 | Low          | M              |
| Medium              | Medium       | H              |
| High                | High         | H              |

**Table 6. Level of disaster risk**

3. Discussion and analysis

The results of the simulation show that almost all sub-districts along the coast have a high inundation depth, with a maximum of > 3m, except Meureubo sub-district, which is characterized by a medium inundation depth within the 1-3 m range. The results are presented in Figure 3.

The area affected by the tsunami was the area surrounding the coast. For West Aceh Regency, it covered Arongan Lambalek, Samatiga, Johan Pahlawan, and Meureubo Regencies, while for Nagan Raya Regency, it span Kuala Pesisir, Tadu Raya, Tripa Makmur and Darul Makmur Regencies. Almost all sub-districts had a high hazard index, except Meureubo (low) and Tadu Raya and Darul Makmur (medium). Figure 4(a) represents the hazard index map for West Aceh and Nagan Raya Regencies.
The disaster risk assessment conducted by Aceh Disaster Management Agency (BPBA) in 2015 characterized the hazard index as high for both West Aceh and Nagan Raya Regencies. The results of our simulation, also assign West Aceh and Nagan Raya Regencies a high hazard index, except in the districts of Meureubo (low), Tadu Raya and Darul Makmur (medium). This discrepancy may be attributed to differences in tsunami location reviews, as the BPBA assessment was carried out at the district level, while this study focused on the sub-district level. In addition, this study used a micro-zonation method, which produced a more detailed hazard index.

Tsunami vulnerability in each region was assessed on the basis of the parameters previously described. Results pointed to both high vulnerability and medium vulnerability indexes, as shown by Figure 4(b).

A high capacity index was found for all affected areas in West Aceh and for Nagan Raya Regencies the capacity index was medium. Inadequate education on disaster and reducing basic risk factors for a tsunami disaster provides an explanation. A capacity index map is presented in Figure 4(c).

From the results of the calculation, all sub-district affected areas received high tsunami risk index results, with the exception of Meureubo, Tadu Raya, and Darul Makmur, which obtained medium index results, as shown by Figure 4(d).

![Image](a) ![Image](b) ![Image](c) ![Image](d)

Figure 5. (a). Hazard Level, (b). Loss Level, (c). Capacity Level, (d). Risk Level

The disaster risk assessment was carried out by assessing and mapping the levels of hazard, loss, and capacity based on the index shown in Table 7. The results described various hazard, loss, capacity...
and risk levels for the affected areas, ranging from low to high (Figure 5). Although tsunami inundation depth was categorized as high, risk levels vary depending on the ratio of the affected area. In Darul Makmur District, tsunami inundation was estimated to affect less than 20% of the area. Because the areas is wider, population development mostly occurs upstream rather than in the coastal zone. Therefore, the population exposed to a potential tsunami would be smaller. Additionally, the unaffected area can be utilized as an evacuation alternative, increasing the capacity of the area. Categorizing Darul Makmur District as medium-level risk is thus more appropriate. This finding demonstrates that micro-zonation risk assessments produce a more detailed and proportional index.

Table 7. Sub-District Index

| Index                        | Sub-District Affected* |
|------------------------------|------------------------|
|                              | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Economic Vulnerability Index | H** | H | H | L | H | H | H | H |
| Physical Vulnerability Index | H | H | H | M | H | H | H | L |
| Social Vulnerability Index   | M | M | H | M | M | M | M | M |
| Environmental Vulnerability Index | M | M | M | M | M | M | M | M |
| Loss Index                   | H | H | H | M | H | H | H | M |

**H (High); M(Medium); L(Low)**

4. Disaster mitigation

As shown in Figure 5(d), tsunami risk for almost all affected sub-districts in West Aceh and Nagan Raya Regencies was categorized as high. This constitutes the primary basis for developing tsunami disaster management plans in West Aceh and Nagan Raya Regencies. Recommendations for non-structural and structural mitigation efforts to increase the capacity value include:

1. Implementing zoning in spatial arrangement, which covers several levels of tsunami-prone/risk zones up to the villages in the whole region of West Aceh and Nagan Raya Regencies;
2. Building government capacity at the level of West Aceh and Nagan Raya Regencies to anticipate tsunami-related emergencies, particularly in areas categorized as high risk, namely Arongan Lambalek, Samatiga, and Johan Pahlawan (West Aceh), and Kuala Pesisir and Tripa Makmur (Nagan Raya);
3. Training disaster management practitioners to respond to tsunami early warning information and communicating it to the wider community;
4. Strengthening the chain of tsunami early warning system, especially on the cultural side of the early warning system and in areas categorized as high risk, namely Arongan Lambalek, Samatiga, and Johan Pahlawan (West Aceh), and Kuala Pesisir and Tripa Makmur (Nagan Raya);
5. Engaging in efforts to improve tsunami preparedness through tsunami evacuation training, the socialization of tsunami-prone areas, and increasing tsunami disaster preparedness in schools and communities. The analysis of the capacity index revealed that education on disasters in the regions under study was of low value, pointing out the necessity of establishing disaster schools there;
6. Constructing tidal monitoring stations to determine the shortest estimated time of arrival (ETA) of tsunami waves in an area targeted for evacuation. The shortest ETA can be calculated by observing water level data at the nearest tidal station and comparing it to levels observed during previous tsunami events;

7. Constructing buildings and tsunami evacuation routes;

8. Implementing the concept of co-benefits of structure, which utilizes certain public buildings or infrastructure (e.g., roads) as urban transportation infrastructure that can contribute to reducing tsunami waves to a certain degree.

5. Conclusions

This study identified the high-risk level of affected sub-districts, namely Aroganlambalek, Samatiga, and Johan Pahlawan (West Aceh District) and Kuala Pesisir, Taduraya and Tripa Makmur (Nagan Raya District). Others sub-districts namely Meureubo (West Aceh) characterized as low risk and for Darulmakmur (Nagan Raya) characterized as medium. The method employed by this area-based risk assessment resulted in more proportional values for each index and level and a more detailed and appropriate risk index and level. By this method, it is expected that the stakeholders will be able to design more specific mitigation plan based on the risk assessment.

Structural and non-structural efforts are required for mitigation, such as improving regional capacity through the implementation of zoning in spatial arrangement, government capacity building, the strengthening of education and early warning systems, and the construction of alternative building designs which can reduce the impact of a tsunami.

References

[1] Aceh Disaster Management Agency 2015. *Aceh Disaster Risk Assessment* 2016-2020.

[2] Al’ala M, Rasyif TM, Fahmi M. Numerical simulation of ujong seudeun land separation caused by the 2004 Indian Ocean tsunami, Aceh-Indonesia. *Science of Tsunami Hazards*. 2015 Jul 1; 34 (3).

[3] Stein S, Okal EA. Speed and size of the Sumatra earthquake. *Nature*. 2005 Mar; 434 (7033): 581-2.

[4] Stein S, Okal EA. Ultralong period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process. *Bulletin of the Seismological Society of America*. 2007 Jan 1; 97 (1A): S279-95.

[5] BN disaster. Regulation of the Head of the National Disaster Management Agency No. 8 of 2011 concerning *Standardization of Disaster Data*.

[6] Tanaka H, Kayane K, Adityawan MB, Farid M. The effect of bed slope to the tsunami intrusion into rivers. *In Proceedings of the 7th International Conference on Coastal Dynamics 2013 16011610*.

[7] Sihombing YI, Adityawan MB, Chrysanti A, Widyaningtias, Farid M, Nugroho J, Kuntoro AA, and Kusuma MA 2019 *Tsunami overland flow characteristic and its effect on Palu Bay Due to the Palu Tsunami 2018*. *Journal of Earthquake and Tsunami*. 14 1-20
[8] Adityawan MB, Tanaka H. Shoreline changes at Sendai port due to the great north East Japan tsunami of 2011. InCoastal Dynamics 2013 Jun (45, No.1, pp. 63-72).

[9] Chrysanti A, Adityawan MB, Yakti BP, Nugroho J, Zain K, Haryanto I, Sulaiman M, Kurniawan A, Tanaka H. Prediction of shoreline change using a numerical model: case of the Kulon Progo Coast, Central Java. InMATEC Web of Conferences 2019 (270, p.04023). EDP Sciences.

[10] Haiqal M, Sari LH, Evalina Z, Hasibuan P. A review of vertical evacuation on tsunami mitigation case. In IOP Conference Series: Materials Science and Engineering 2019 May (523, No.1, p. 012061). IOP Publishing.

[11] Harits M, Safitri R, Nizamuddin N. Study of Preparedness for the Aceh Disaster Management Agency in the of the Tsunami Disaster in Aceh Province. International Journal of Multicultural and Multireligious Understanding. 2019 May 27; 6 (2): 644-57.

[12] Mitobe Y, Adityawan MB, Roh M, Tanaka H, Otsushi K, Kurosawa T. Experimental study on embankment reinforcement by steel sheet pile structure against tsunami overflow. Coastal Engineering Journal. 2016 Dec 1; 58 (4): 1640018-.

[13] Mitobe Y, Adityawan MB, Tanaka H, Kawahara T, Kurosawa T, Otsushi K. Experiments on local scour behind coastal dikes induced by tsunami overflow. Coastal Engineering. 2014: 2.

[14] National BP. Regulation of the Head of the National Disaster Management Agency Number 02 of 2012 concerning General Guidelines for Disaster Risk Assessment. BNPB. Jakarta. 2012.

[15] Regulation of the Head of the National Disaster Management Agency, General Guidelines for Disaster Resilient Villages, (Jakarta: BNPB, 2012), p. 24

[16] Kusuma MS, Adityaman MB, Farid M. Modeling Two Dimension Inundation Flow Generated by Tsumani Propagation in Banda Aceh City.

[17] Yakti BP, Adityawan MB, Farid M, Suryadi Y, Nugroho J, Hadihardaja IK. 2D modeling of flood propagation due to the failure of way Ela natural dam. InMATEC Web of Conferences 2018 (147, p. 03009). EDP Sciences.

[18] Disaster, BNP, 2016. Indonesia's Disaster Risk. Jakarta, DKI Jakarta, Indonesia.

[19] Farid M, Gunawan B, Kusuma MS, Habibi SA, Yahya A. Assessment of Flood Risk Reduction in Bengawan Solo River: A Case Study of Sragen Regency. International Journal. 2020 Jun; 18 (70): 229-34.

[20] Prasetya, G., Borrero, J., de Lange, W. et al. Modeling of inundation dynamics on Banda Aceh, Indonesia during the great Sumatra tsunamiis December 26, 2004. Nat Hazards 58, 1029 – 1055 (2011).

[21] Tanioka Y, Caseose T, Kathioli S, Nishimura Y, Iwasaki S, Satake K (2006) Rupture process of the 2004 great Sumatra-Andaman earthquake estimated from tsunami waveforms. Earth Planet Space 58: 203–209

[22] Latief H. An assessment of the tsunami risk in West Sumatra Province and its mitigation efforts. InProceedings of the 37th HAGI Annual Convention and Exhibition (Palembang) 2012 Sep 13.
Acknowledgement

The authors would like to acknowledge the support given by Institute for Research and Community Services of Institut Teknologi Bandung through 2020 Multidisciplinary Research with the title of “Development of Tsunami Propagation Models for Built Coastal Areas (Pengembangan Model Rambatan Tsunami untuk Kawasan Pantai Terbangun)".