ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of Geography Vol.54 , No. 1, 2022 (62 – 69)
DOI: http://dx.doi.org/10.22146/ijg.66500 website: https://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY

RESEARCH ARTICLE

A New Approach of the Tsunami Mitigation Strategies for the City of Banda Aceh, Indonesia

Halis Agussaini[1,2*], Sirojuzilam[1], Rujiman[1] and Agus Purwoko[1]
[1]Doctoral Program of Regional Planning, Universitas Sumatera Utara, Jl. Dr. T. Mansyur No.9, 20155, Medan, Indonesia, [2]Department of Architecture and Planning, Universitas Syiah Kuala, Jl. Tgk. Syech Abdurrauf No. 7, Banda Aceh 23111, Indonesia

Received: 2021-08-04
Accepted: 2022-01-31

Keywords:
spatial planning;
tsunami mitigation strategies;
coastal areas;
Banda Aceh City

Correspondent email:
halisagussaini@unsyiah.ac.id

Abstract. Ten years after rehabilitating and reconstructing some coastal areas of Banda Ache struck by the tsunami, and the city is currently repopulated, with most of its open land and community ponds converted into settlements. This rise in population needs to be controlled to minimize damages and casualties, assuming the tsunami hits again. Presently, the Banda Aceh City spatial plan for 2029 does not have a clear concept of tsunami mitigation, specifically in the spatial pattern of coastal areas. Therefore, this research aims to remap the vulnerability level of the Banda Aceh City coastal area from the tsunami hazard and determine alternative strategies based on the tsunami level in achieving safe, comfortable, productive, and sustainable spatial planning goals. This starts by analyzing the wave height generated by the earthquake that triggered this natural disaster and mapping the spatial distribution of the area and the tsunami's inundation height. The results showed that the proportionate regions prone to Level-2 tsunami were worse than the 2004 disaster based on the water level markers built in the city. The spatial planning strategies for the coastal area of Banda Aceh City are carried out by determining the level of tsunami-prone and the potential of the area's resources through a new approach of the multi-layer tsunami defence systems by combining sea dike, greenbelt, silvo-fishery, and the elevated road.

1. Introduction

The tsunami wave that struck Aceh on December 26, 2004, was one of the biggest natural disasters in the modern age, killing more than 89,000 people, with approximately 132,000 still missing (Tejakusuma, 2005). This natural disaster caused damage to 1.3 million houses and buildings, 8 ports, 4 fuel deportations, 85% water channels, 92% sanitation systems, 120 km of roads, and 18 bridges. According to (National Development Planning Agency (2005), the damage and losses were estimated at Rp.42.7 trillion. After ten years of restoration and reconstruction (2009-2019), Banda Aceh has developed rapidly, inseparable from its role as the provincial capital, business service, and education city. Physically, the built-up area increased by 2.5%, and the population grew rapidly, reaching 265,111 people (BPS Banda Aceh, 2019), surpassing its initial 265,098 people before the 2004 tsunami (BPS Banda Aceh, 2006). Coastal areas are expected to contribute to improving the city's economy, in addition to protecting against natural disasters in coastal areas. Territorial development and growth constraints are often factored into spatial planning for disaster risk management (Hasyim et al., 2014).

The tsunami had been a driving factor for population migration from the coast, but due to other factors such as low land prices, urban residents selected to live in the area (Akbar and Ma'rif, 2014; Syamsidik et al., 2017; McCaughey et al., 2018). This is represented by the conversion of 33.32% pond land to other uses, of which 22.67% was utilized for residential purposes (BPS Banda Aceh, 2019). Achmad et al., (2015) predicted the growth of cities towards the coast, where socio-economic factors dominate and promoted the increase in built-up areas affected by the tsunami. The future possibility of this wave hitting Aceh again was suggested by Sieh et al. (2014) based on geological and archaeological evidence of ancient tsunamis and from the results of paleoseismology and paleo-tsunami research conducted by Natawidjaja (2015). This finding is not only a warning of the possible repeat of the 2004 event that caused tremendous damage to lives and properties. Rather it is an indicator that the city does not follow the principles of sustainable development because a major natural disaster can erase the progress made and take years to rebuild (Uitto and Shaw, 2016).

Since tsunamis are still rare in Indonesia, Banda Aceh did not include a mitigation aspect in its spatial planning patterns before its occurrence. However, after the tsunami, the spatial planning unsuccessfully changed to the rehabilitation and reconstruction period, specifically in coastal areas, where residential buildings with a radius of 500 m were identified as protected regions in the form of green belts. One of the causes of this failure was the government's inability to provide another place that guarantees the economy of the citizens (Susanto, 2014). After rehabilitation and reconstruction, coastal spatial planning became more accommodating by allowing the construction of new fishing and low-density housing estates through the construction of escape buildings and route facilities as a containment strategy, though it is still considered vulnerable to tsunami threat (Kurniawan and

Wijaya, 2013; Syamsidik et al., 2017). Presently, there is no significant difference in the spatial planning (RTRW) of the 2009-2029 revision 2017 in reducing the level of tsunami-prone. This means that land-use change is insufficient to reduce the tsunami's impact as the only mitigating factor.

After the Great Tsunami that struck the city of Sendai on March 11, 2011, tsunami waves were classified into two different levels based on the frequency of events and its associated height in accordance with the earthquake magnitude, i.e., Level-1 and Level-2. This classification aims to define an appropriate mitigation model for the application. Level-1 tsunami represents the wave frequency for 100-years resulting in relatively low (less than 10 m) inundation depth. Meanwhile, the Level-2 tsunami for evacuation model, which represents the frequency events for 1000-years, has relatively high submersion depths of more than 10 m (Suppasari, 2012; Shibayama et al., 2013; Sato, 2015; Bhattacharya et al., 2017).

Previous research on tsunami risk and mitigation efforts by Jokowinarno (2011), (Muhari et al (2012), and Pratomo and Rusiarto (2013) stated that practicality needs to be improved by developing more specific spatial planning strategies. Similarly, mitigation research using coastal vegetation structures by Yanagisawa et al (2010), Fuady (2015); and Edyanto (2019) are still generic and have not been accounted for based on tsunami frequency and wave heights. Pakoksung et al (2018) proposed the latest research as a tsunami mitigation strategy based on its impact on Sendai City in 2011. The layered defence concept is based on structured computing scenarios and 24 cases of simulated tsunami protection in Sendai City. The combination of existing and new seawalls, green belts, elevated roads, and highways was used to withstand the tsunami that hit Japan in 2011. However, this research did not consider the resource potential of the area.

Based on the description above, it is necessary to conduct research to remap the vulnerability level of the Banda Aceh coastal area from the tsunami hazard. This is conducted based on the classification of the tsunami level to determine alternative strategies generated by the triggering earthquake and evaluate regional resources' potential to achieve the goal of safe and sustainable spatial planning.

2. Methods

Location

This research was conducted in the administrative area of Banda Aceh City, Aceh, Indonesia (Figure 1), which is geographically located between 05o30' – 05o35' north latitude and 95o30' – 99o16' east longitude. The altitude of the city ranges from 0.45 m - 1.00 m above sea level, with an average height of 0.80 m. The land surface (physiography) is relatively flat, with a slope between 2% - 8%.

Banda Aceh City is located at the intersection of the Eurasian and Australian plates, about 130 km away from the western coastline; therefore, it is prone to tsunamis (Diposaptono, 2014). Based on the inundation area due to the 2004 tsunami, the government of Banda Aceh City designated four coastal areas as tsunami-prone regions in its regional spatial plan (Banda Aceh City Government, 2009). However, this provision was later changed in the revised regional spatial plan by designating the entire area as vulnerable to the wave (Banda Aceh City Government, 2018). There is no explanation regarding the change in the determination, but it is possible based on the recommendations of recent research related to the city's tsunami hazard level.

Procedure

This research starts by determining the tsunami's height, which is generally triggered by earthquakes on the seabed at a depth of less than 60 km from an ascending or descending fault type with a magnitude above 6 Mw (S. Hidayatullah, 2015). The tsunami height is needed to classify its levels based on the magnitude of the associated triggering earthquake. This utilized the magnitude from the 2004 tsunami, which ranged from 7.0 Mw to 9.0 Mw, namely 7.0

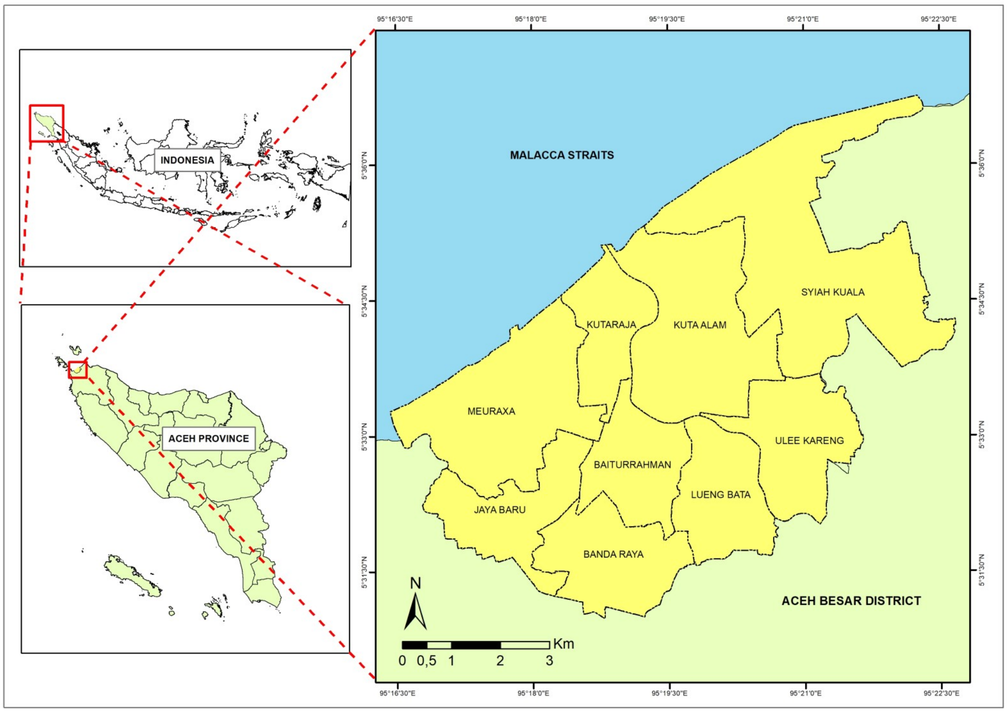

Figure 1. Research Area Map

Mw, 7.5 Mw, 8.0 Mw, 8.5 Mw, and 9.0 Mw. The generated height by the magnitude of the earthquake in Indonesia can be calculated by referring to the Public Work Ministerial Decree No. 6/2009 (Indonesian Government, 2009), which uses Abe's equation as follows:

Log (Hr) = 0.5 Mw – 3.3 + C ……………………………………………(1)

where Hr is the limit tsunami height (meter), Mw is the earthquake magnitude, and C is a constant, (C = 0 for the fore-arc and C = 1 for the back-arc). The maximum run-up height (Hm) is expressed by the following equation:

Hm = 2 Hr ……………………………………………………………………(2)

The next step is to create a tsunami hazard map for Banda Aceh City using the (Berryman, 2006) equation. The parameters used include the height of the incoming wave (run-up), the slope value, and surface roughness. The run-up, slope value, and surface roughness were obtained from equation (2), Digital Elevation Model (DEM) data processing, and land cover analysis processed by high-resolution satellite imagery in 2017. The equation is formulated as follows:

$$H_{loos} = \left(\frac{167n^2}{Ho^{1/3}}\right) + 5\,sin\,S$$

where Hloos is the decrease in the amount of water entering the land per 1 meter of inundation distance, Ho is the tsunami wave height in the coastline, S is the slope in degrees, and n is the Manning surface roughness coefficient (Kalyanapu et al., 2009; Bunya et al., 2010; Kaiser et al., 2011; Liu et al., 2019) . The equation is processed using a model builder and adding the Geographic Information System (GIS) to generate Hloss. The distribution of inundation is obtained through a cost distance mathematical process by entering the run-up height parameter, annotated as Ho (Purbani et al., 2013), where its value equals Hm. The tsunami hazard index refers to the annexe of the National Disaster Management Agency No. 2/2012 (BNPB, 2012), which divides the disaster index into three classes, namely: (1) low (no prone), (2) moderate (prone), and (3) high (very prone) assuming the depths are below 1 meter, approximately 1-3 meters and above 3 meters.

Table 1. The Relationship between The Magnitudes of The Earthquake and the Height of The Tsunami

Earthquake magnitudes (Mw)	Run-up heights (m)
7.0	3.16
7.5	5.62
8.0	10.02
8.5	17.82
9.0	31.69

3. Result and Discussion

The Tsunami Height Caused by Earthquake Magnitudes

The tsunami waves' height due to the magnitudes of the earthquakes is shown from equations (1) and (2) in Table 1. Based on the wave height generated in Table 1 above, Levels-1 and -2 tsunami were obtained by earthquakes below and above 8.0 Mw, respectively.

Inundations Area and Levels of Tsunami-Prone

The inundation area caused by Level-1 tsunami (8.0 Mw earthquake as the maximum magnitude) and Level-2 tsunami (9.0 Mw earthquake in 2004) was calculated using equation (3). Furthermore, the results of the tsunami inundation areas are then classified based on the level of proneness, as shown in Table 2 as well as Figures 1 and 2. The numerical tsunami simulation results show that the higher the incoming waves, the wider the inundated areas. This research's difference in the tsunami waves' height shows that varying altitudes strongly influence the affected areas. The tsunami wave height of 10.02 m inundated the land at a very prone (R3), prone (R2), and none-prone (R1) areas of 1,736.06 ha or 29.42%, 3,068.94 ha or 52.01%, and 1,198.48 ha or 20.31%, respectively. Meanwhile, at a tsunami wave height of 31.69 m, the land was inundated with a very prone (R3), prone (R2), and non-prone (R1) levels covering areas of 1,812.89 or 30.73%, 3,119.38 ha or 52.87%, and 1,090.97 ha or 18.49%, respectively. The inundation area at this height is worse than the 2004 tsunami according to the water level markers built in Banda Aceh City (Iemura et al., 2008), as shown in Figure 4. Many natural coastal protectors, such as mangroves and other plants damaged in 2004, have not been fully replanted.

The Tsunami Multi-Layer Defence Systems

The multi-layer tsunami defence systems are designed based on velocity and inundation (Pakoksung et al., 2018), which are influential in reducing damages due to the wave (Risi et al., 2017). According to Syamsidik et al. (2019), reducing the wave's velocity and inundation due to natural and man-made structures has been proven correct by previous researchers, namely Matsutomi et al. (2010) and Nandasena et al. (2012). The concept of tsunami countermeasures combines structure-based flood protection designed for Level-1 tsunami and non-structure-based damage reduction planned for Level-2 tsunami for disaster mitigation (Kobayashi et al., 2015; Koshimura and Shuto, 2015; Sato, 2015).

The multi-layer tsunami defence systems implemented in Sendai City after the Great Earthquake and 2011 Tsunami in Japan can also be applied in Banda Aceh City, with several modifications to suit its morphological, environmental, social, and financial conditions. Table 3 provides a detailed

Table 2. The Inundation Areas and The Tsunami Hazard Levels in Banda Aceh City

Earthquake magnitudes (run-up height)	Inundation areas based on the levels of tsunami hazard					
	R1 (no prone <1 m)		R2 (prone 1-3 m)		R3 (very prone >3 m)	
	ha	%	ha	%	ha	%
8.0 Mw (10.02 m)	1,198.48	20.32	2,965.66	50.26	1,736.06	29.42
9.0 Mw (31.69 m)	967.93	16.41	3,119.38	51.21	1,812.89	32.38

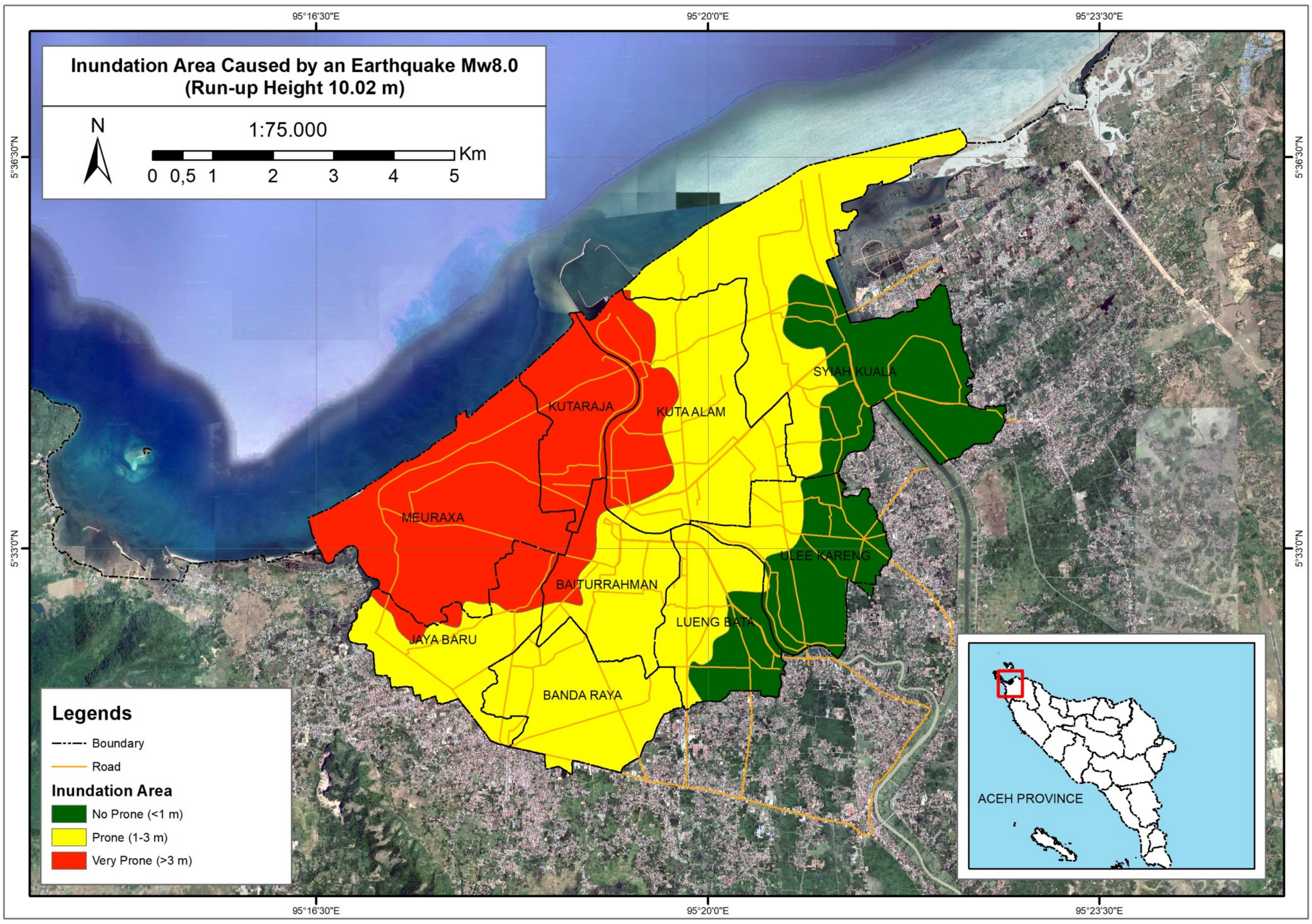

Figure 2. Map of Tsunami Inundation Level-1 (8.0 Mw)

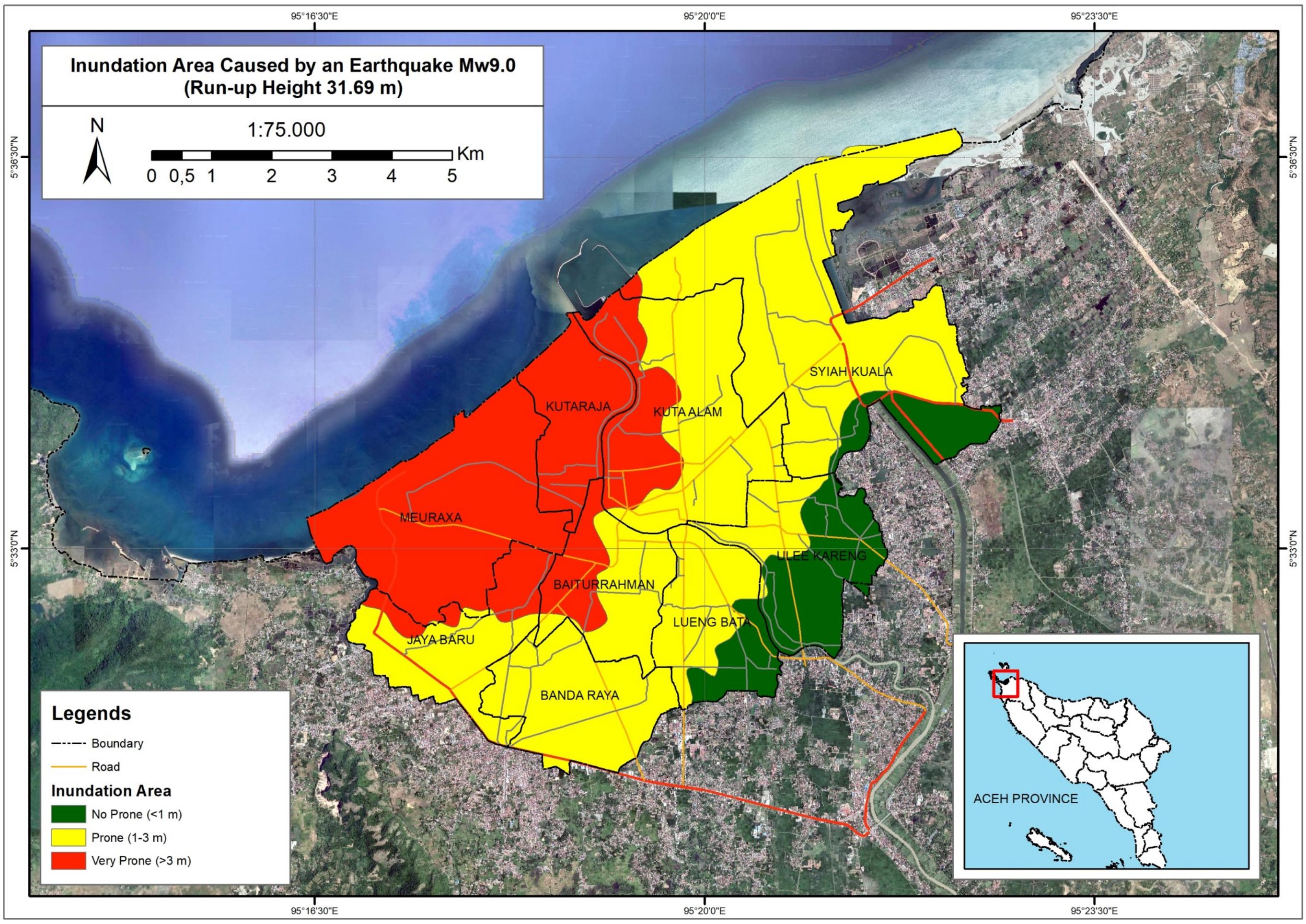

Figure 3. Map of Tsunami Inundation Level-2 (9.0 Mw)

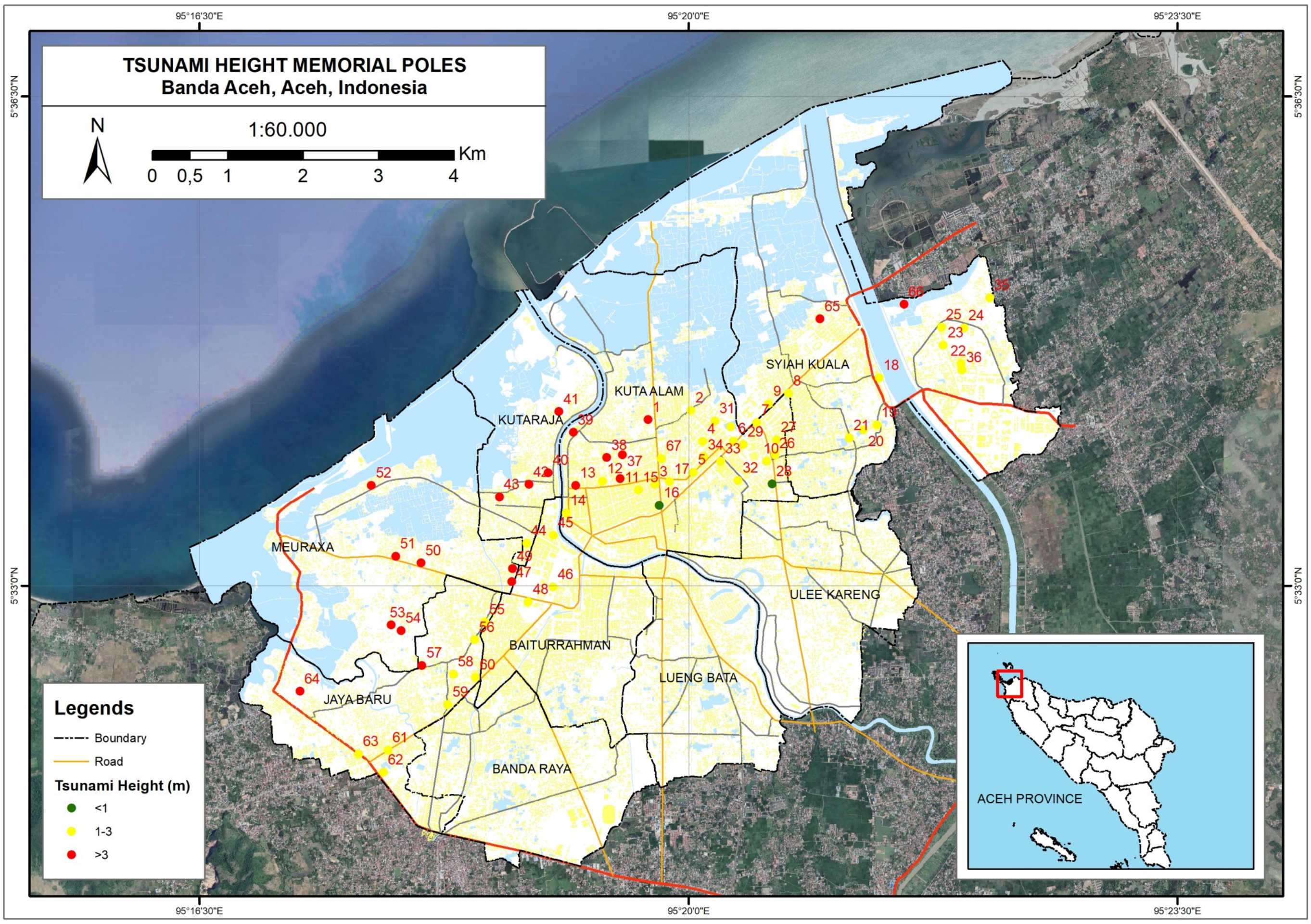

Figure 4. Map of TheWater Level Markers Built in Banda Aceh City

description of tsunami mitigation strategies levels in this research.

Level-1 tsunami (protection) strategy is planned for the coastal area of this city through the multi-layer tsunami defence systems, as follows:

Layer-1:

Strengthen and maintain the existing breakwater and sea dikes, which protect against sea-level rise and tidal flooding. However, these structures are not significant to protect against tsunami (Esteban et al., 2015), but they can reduce the shallow effect (Suppasri et al., 2016; Lampela, 2021). The sea dikes' heights follow the sea level rise due to global warming, as opposed to seawalls that need large funds (Linham and Nicholls, 2010) and have a negative impact by reducing the visual appeal of the beach (Shibayama et al., 2013). Sea dikes have the least environmental and economic impact (Nikoo et al., 2014).

Layer-2:

Establishing greenbelts of mangroves by freeing land along the coastline of at least 100 m from the highest tide point and providing area by around 150 m to the coastal forest. According to Tanaka (2009) and Esteban et al (2015), mangroves and coastal forests play key roles in reducing the effect of natural disasters, such as tsunamis. Danielsen et al. (2005) stated that a dense mangrove of *Rhizophora spp.* and *Avicennia spp.* (density = 14-26 tree trunks per 100^2 m) decreased damage in 96% of surveyed cases in India. Similarly, Hiraishi and Harada (2003) stated more than a 90% reduction in maximum tsunami flow pressure by a 100 m–wide forest belt when the tree density increased (30 tree trunks per 100 m^2). Tanaka (2012) reported that the breaking phenomena of trees estimate the capacity of a coastal forest to reduce the washout region of houses around 150 m by setting at 10 m (Level-1 tsunami) of the maximum tsunami water depth at the shoreline. The combination of mangroves and coastal forests can also be used for ecotourism activities by involving local communities as managers, thereby increasing their economy and efforts to meet the needs of urban green open space.

Layer-3:

Changing the opened ponds into the silvo-fisheries system using *komplangan* modification with the alternating arrangement is part of the tsunami hazard mitigation efforts. An open pond system with large standing water creates gaps, thereby enabling the washed debris to cause damage to the buildings (N. Tanaka, 2012). Various research on the silvo-fishery system's choice also shows that it is more profitable than an open pond system from an ecological, social, and economic perspective (Shilman, 2012; Pangarevo, 2017).

In this area, fishing settlement with very low and limited density is still permitted. However, it is only reserved for fishermen, and the construction of the house on the ground was returned to a stilt (rumoh Aceh) which has local wisdom values for earthquake and tsunami disaster mitigation (Hairumini et al., 2017).

Layer-4:

The Banda Aceh Outer Ring Road (BORR), originally planned as an alternative road to reduce traffic congestion in the city centre, is designed as a protection structure

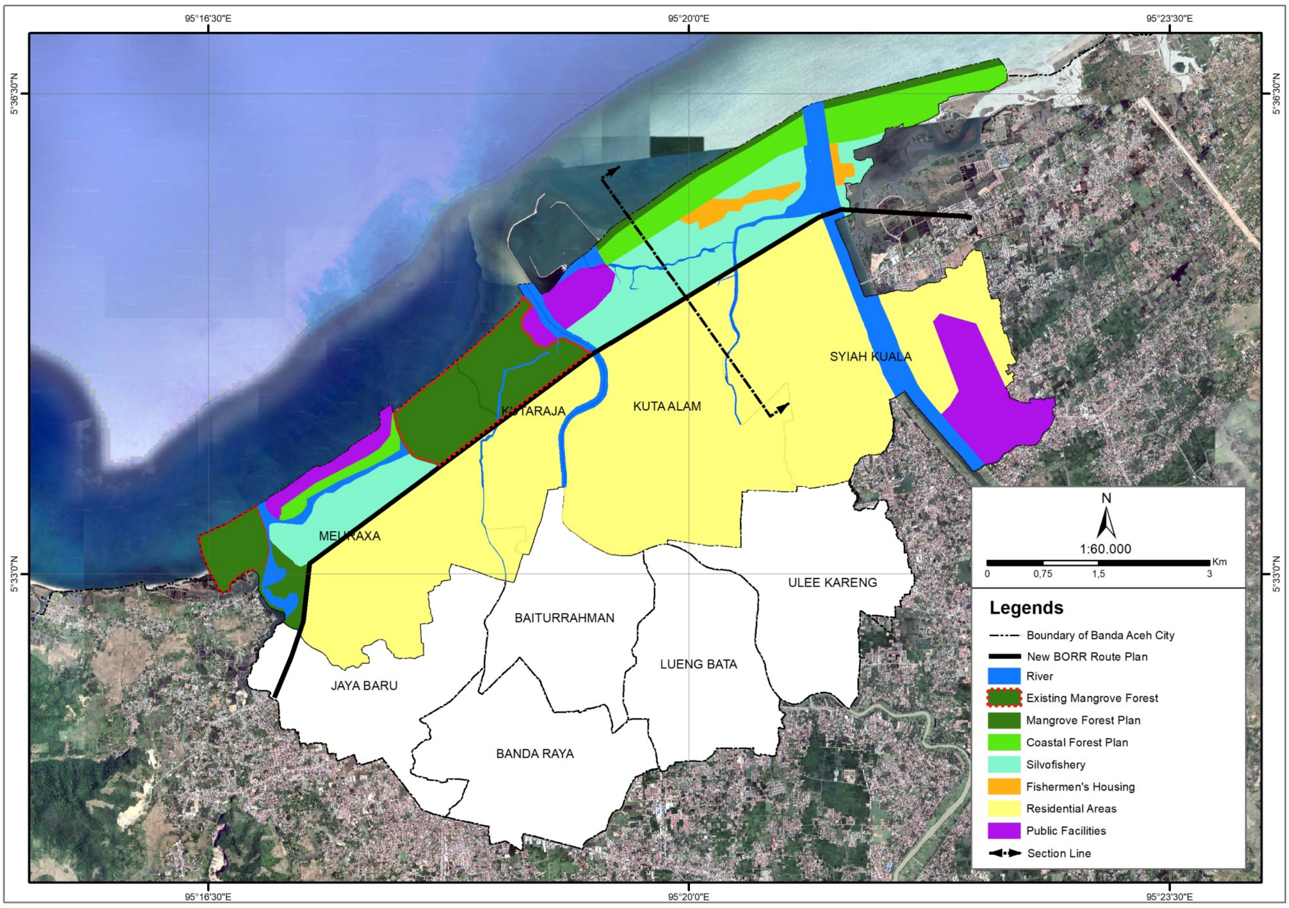

Figure 5. Conceptual Illustration of A New Approach of Tsunami Mitigation Strategies to Reduce The Risk of Tsunami Disasters and to Optimize The Resources Through The Multi-Layer Defence Systems

Table 3. Description of Tsunami Mitigation Strategies Levels

Mitigation strategies	Description of strategies	
	Sendai City (Kobayashi et al., 2015; Koshimura and Shuto, 2015; Pakoksung et al., 2018)	Banda Aceh City (authors' modification)
Level-1 tsunami (protection)		
Layer-1	Strengthen the existing sea wall and build a new sea wall.	Strengthen and maintain the existing breakwater and sea dikes.
Layer-2	Establish coastal forests as a greenbelt (coastal protection forest).	Establish mangroves and coastal forests as greenbelt (coastal protection forest).
Layer-3	Build a park (artificial hill).	Convert ponds into silvo-fisheries; Allow housing for fishermen with special requirements (such as the shape of the house on stilts).
Layer- 4	Build elevated roads to minimize the potential losses.	Elevate the ring road to reduce the potential losses.
Level-2 tsunami (evacuation)		
		Move settlements from high to low-risk areas affected by the tsunami. Does not allow new housing in high-risk areas affected by the tsunami.
	Establish evacuation sites to protect citizens' lives.	Establish locations of evacuation in safe zones.

against tsunami waves by raising it 5 m above sea level (S. Tanaka et al., 2010; Koshimura and Shuto, 2015). The route was shifted behind the silvo-fisheries at 1,000 m from the coastline, which was originally approximately 800 m. The recent research by Syamsidik et al (2019) showed that elevating a road's height by 5 m from the original route reduces the inundation area by approximately 22% in the case of 8.5 Mw earthquakes.

Level-2 tsunami (evacuation) strategy planned for the coastal area of Banda Aceh City is to provide evacuation

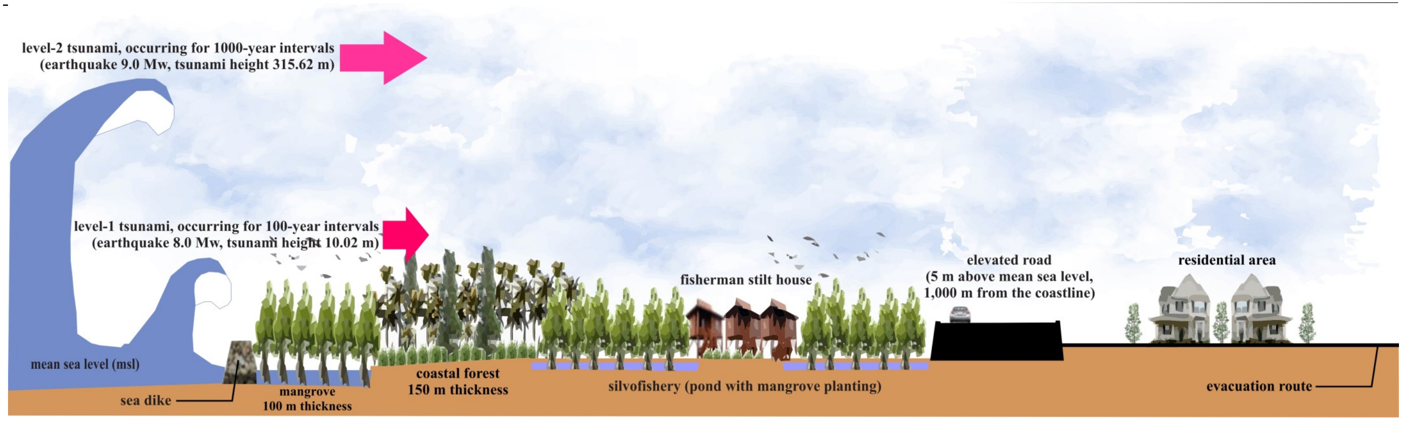

Figure 6. Conceptual Illustration of A Section of A New Approach of Tsunami Mitigation Strategies to Reduce The Risk of Tsunami Disasters and To Optimize The resources Through The Multi-Layer Defence Systems

routes and sites, which must be in a safe zone against tsunami hazards, have easy accessibility, clean water, sanitation facilities, and meet the standards set by disaster management agencies (BPB Aceh, 2017). The strategic concept of the two tsunami levels is shown in Figures 5 and 6.

4. Conclusion

Tsunamis are recurring events that occur once in 100 (Level-1 tsunami) or 1000 years (Level-2 tsunami). Therefore, based on an analysis of inundation areas using Level-2 tsunami, the flooded and vulnerable areas were worse than the 2004 tsunami because many natural coastal protectors such as mangroves and other previously damaged plants have not been damaged been fully replanted. Banda Aceh City's coastal tsunami mitigation strategies are dedicated to Level-1.

The Banda Aceh City's government needs to consider the strategies formulated above in preparing the next round of the Banda Aceh City RTRW revision for 2009-2029. This is because it is built on the perspective of resilience and prevention or reduction of disaster risk to achieve balanced environmental sustainability, increase the overall well-being and provide a sense of security among communities living in the coastal zone.

This research is limited to GIS software for the cost distance tools to generate tsunami hazard maps and uses simple calculations based on previous research. Therefore, further research needs to estimate the earthquake's magnitude, the extent of the tsunami vulnerability, and the ability to obtain an accurate protective protection structure in coastal areas at risk of this natural disaster.

Acknowledgement

This paper is part of doctoral research at Universitas Sumatera Utara, Medan. The authors are grateful to Universitas Syiah Kuala for supporting this research and the Ministry of Research, Technology, and Higher Education of Indonesia Scholarship for their financial support.

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