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RESEARCH ARTICLE

Modeling the Potential of Tsunami Hazard in Labuan Bajo Towards A Disaster-Resilient Tourism Area

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Abstract. In 2019, Labuan Bajo was designated a super-priority tourism destination, but this area is prone to earthquakes and tsunamis. The potential threats of disasters need to be considered when developing the tourism sector. Therefore, this study aims to determine the height and arrival time of tsunami waves based on a worst hypothetical scenario on the north coast of Labuan Bajo and its surroundings. The method used was numerical modelling with open source software TUNAMI F1, which calculated the wave propagation based on linear equations in spherical coordinates based on worst scenarios. The results showed that the Flores back-arc thrust earthquake caused a reasonably high tsunami with a fast arrival time at Labuan Bajo. The wave height of the tsunami around Labuan Bajo, Rinca, and Komodo Island is at least 3 m, but it reaches 8-9 m under certain conditions. Furthermore, its arrival time on the coast of Labuan Bajo is less than 2.5 minutes. This is much faster than those in Aceh (2004), Pangandaran (2006), and Palu (2018). Even though the early warning came 5 minutes after the earthquake, a high level of preparation and awareness is required to create a disaster-resilient tourist area in Labuan Bajo.

1. Introduction

Labuan Bajo is one of the most famous tourist destinations in East Nusa Tenggara Province of Indonesia. It is located in the West Manggarai Regency and is made famous by the Komodo Island National Park (Figure 1). This area which is one of the 10 National Tourism Strategic regions (KSPN) or "10 New Balis," was established by the government through Presidential Regulation No. 3 of 2016 (Presiden Republik Indonesia, 2016). Furthermore, it was narrowed down to 5 super-priority tourism destinations in 2019, including Labuan Bajo. In 2018, the government created the Tourism Area Management Authority of Labuan Bajo Flores (Presiden Republik Indonesia, 2018). In response to the presidential regulation, the Ministry of Tourism issued a decree on the Organization and Operation of the Implementing Agency of the Labuan Bajo Flores Authority-Badan Pelaksana Otorita Labuan Bajo Flores (BPOLBF) (Kementerian Pariwisata Republik Indonesia, 2018).

This status is followed by various government programs to support and promote tourism development in Labuan Bajo. Currently, the government, through the Ministry of Public Works and Housing (PUPR), organizes and develops the "National Tourism Strategic Area (KSPN)," namely Super Priority Labuan Bajo, East Nusa Tenggara, in particular, the development of infrastructure supporting tourism activities (BPIW, 2020). In 2020, the KSPN was organized by allocating a 1.3 trillion budget (Bahfein, 2020).

Labuan Bajo is located on the west side of the East Nusa Tenggara region and is geographically bordered by the Flores Sea in the north and the Indonesian Ocean and the Australian continent in the south. The meeting of these two plates is convergent, where the Indo-Australian infiltrates the Eurasian. This movement causes these areas in Indonesia to have a relatively high level of seismicity in plate collision activities (plate collision) (National Center for Earthquake Studies-Indonesia-PUSGEN, 2017).

Additionally, areas of Nusa Tenggara are very prone to earthquakes due to a tectonic activity of the island's back arc thrust fault, which occurred due to subduction between the Eurasian and the Indo-Australian Ocean Plate. (Hamilton, 1979) stated that "The phenomenon of arc-continent collision is the upward fault deformation mechanism controller." The longitudinal back-arc thrust in the Flores Sea is divided into 5 segments and extends parallel from Bali in the west to the Wetar islands in the east. Furthermore, the phenomenon of the back-arc fault is interesting to study, considering its activeness in generating earthquakes and tsunamis in the area.

The province of NTT (including Labuan Bajo) is also prone to tectonic earthquakes and tsunami hazards. From 1814 to 2009, out of 27 destructive earthquakes, 13 or 48% were accompanied by waves (Triyono, Prasetya, Daryono, et al., 2019; Triyono, Prasetya, Dewi, et al., 2019; WinITDB, 2007). The first tsunami was recorded to have hit Kupang Bay in 1814, while the last, which resulted in the most significant number of fatalities, occurred on December 12, 1992, with an epicentre located on 8,48^{o}S- 121.93^{o}E, 15 km deep and 7.5 on the Richter scale. Therefore, it caused thousands of

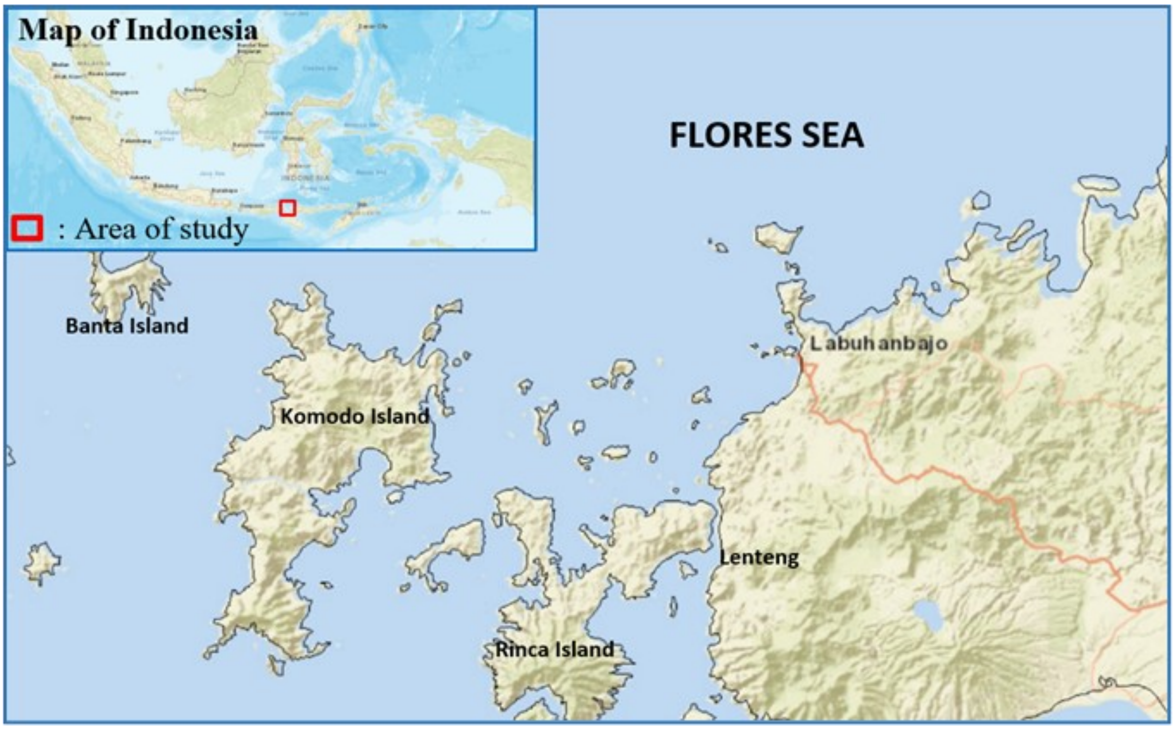


Figure 1. Location of the study

lives and enormous property losses (Triyono, Prasetya, Daryono, et al., 2019; Triyono, Prasetya, Dewi, et al., 2019; WinITDB, 2007; Yeh et al., 1993).

The potential hazards of disasters need to be considered when developing an area, especially in the tourism sector. Government regulation recommends that "the spatial planning is based on disaster mitigation because Indonesia is a prone area" (Indonesia Government, 2017). Regulation by the Minister of Agrarian Affairs and Spatial Planning/ Head of the National Land Agency states that "to determine coastal border protected region tsunami-prone areas need to be considered" (Menteri Agraria dan Tata Ruang, 2018). However, studies and simulations of unique tsunami models in northern Labuan Bajo have never been conducted. Until now, a simulation of the propagation of the 1992 Flores tsunami located in the east of Labuan Bajo is the study conducted (Yeh et al., 1993). Afterwards, the potential for a tsunami in the north of the island of Bali, which is located west of Labuan Bajo, was simulated (Felix et al., 2021; Wibowo, Kongko, Hendriyono, & Karima, 2021). Another study showed the potential for a tsunami originating from Sletan Nusa Tenggara (Pradjoko & Muhari, 2020). Meanwhile, studies directly related to Labuan Bajo are mostly linked to tourism development in terms of potential, policy, socio-economic, urban development, and tourist potential (Akhrani & Azhar, 2021; Andriani Moi, 2017; Idris, Selva, & Destari, 2019; Sugiarto & Gusti, 2020). Therefore, it is essential to study the potential for a tsunami in the north of Labuan Bajo. This study aims to know the tsunami wave height and its arrival time based on the worst hypothetical scenarios.

The results are expected to provide greater awareness to all stakeholders in Labuan Bajo; hence, the desire to make this town a super-priority tourism area is fully achieved. Additionally, the results are expected to be considered in the preparation of contingency plans and mitigation actions to minimize risks when a tsunami occurs.

This study used simulation and numerical modelling of the tsunami caused by tectonic earthquakes in the "Flores Backarc Thrust" through the TUNAMI Model. This has been used for several events in the world with good results. It has been validated using the tsunami incident in Pangandaran on July 17, 2006 (Rahmawan, Ibrahim, Mustofa, & Ahmad, 2012). The results of the TUNAMI model are similar to previous studies and the Agency for Meteorology, Climatology, and Geophysics (BMKG) survey. The average difference in wave height between the simulation and the survey results is 0.98m (20.74%) (Mardi, Malek, Liew, & Lee, 2015; Rahmawan et al., 2012). Mardi et al., 2015 stated that "the TUNAMI, TUNA, COMCOT, MOST, and ANN Tsunami Forecast models had been used to simulate tsunamis based on the Sumatra-Andaman event." (Adriano, Fujii, & Koshimura, 2018) The TUNAMI model was used to simulate the Sendai tsunami on November 22, 2016, through 2 models of earthquake sources. The results were compared with the measurement data and obtained an NRMSE value of 0.686 - 0.863 (Adriano et al., 2018).

2. Methods

TSUNAMI Model

Imamura from Tohoku University developed TUNAMI (Tohoku University's Numerical Analysis Model for Investigation) model. It is "a tool for modeling wave propagation based on linear equations in spherical coordinates and does not consider non-linear terms such as basic roughness" (Fumihiko Imamura, Yalçiner, & Ozyurt, 2006).

The impact of the tsunami wave motion was estimated and quantified using numerical modeling with assumptions, such as "tsunami waves propagate in the form of long waves, the water particles do not have a vertical acceleration, and the water pressure is due to gravity" (Fumihiko Imamura et al., 2006).

Several basic equations are used to model tsunamis. The modeling of tsunami waves uses an equation based on the law of mass conservation applied to incompressible fluids (Goto & Ogawa, 1997; F Imamura, 1996). The initial wave height is required for the input tsunami modeling setup. This is simulated on the fault parameters, such as length and width of the fault, earthquake magnitude (energy), epicentre depth, strike, dip, and slip angle. The earthquake source generates the initial tsunami waves height before propagation (F Imamura, 1996; Wells & Coppersmith, 1994).

Build Model Scenarios

A hypothetical scenario was used based on the Indonesia Earthquake Source & Hazard Map (National Center for Earthquake Studies-Indonesia-PUSGEN, 2017). Figure 2 shows two segments of the earthquake source that significantly affect the Labuan Bajo area and its surroundings. These segments are Lombok Sumbawa Backarc Thrust and Flores Backarc Thrust NT West. Lombok Sumbawa Backarc Thrust has a potential magnitude of Mw 8.0 and movement rate of 9.9 mm/yr, whereas the second has a possible magnitude of Mw 7.5 and movement rate of 6.6 mm/yr

Two hypothetical scenarios for the worst tsunami-generating earthquake source were prepared based on the potential earthquake source. The first scenario's earthquake and tsunami source is Flores Backarc Thrust West NT, while the second is from Lombok Sumbawa Backarc Thrust (Table 1 and Figure 3).

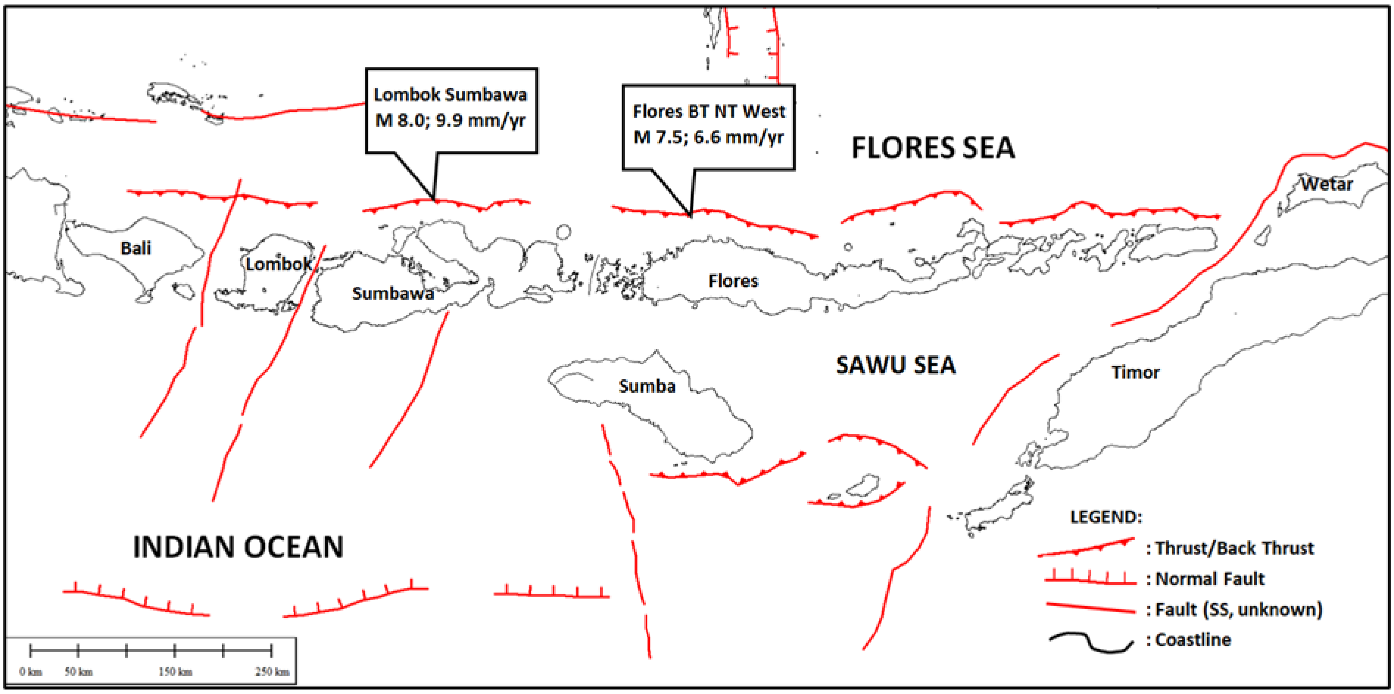


Figure 2. Two segments of the source of the tsunami generating earthquake near Labuan Bajo (National Center for Earthquake Studies-Indonesia-PUSGEN, 2017).

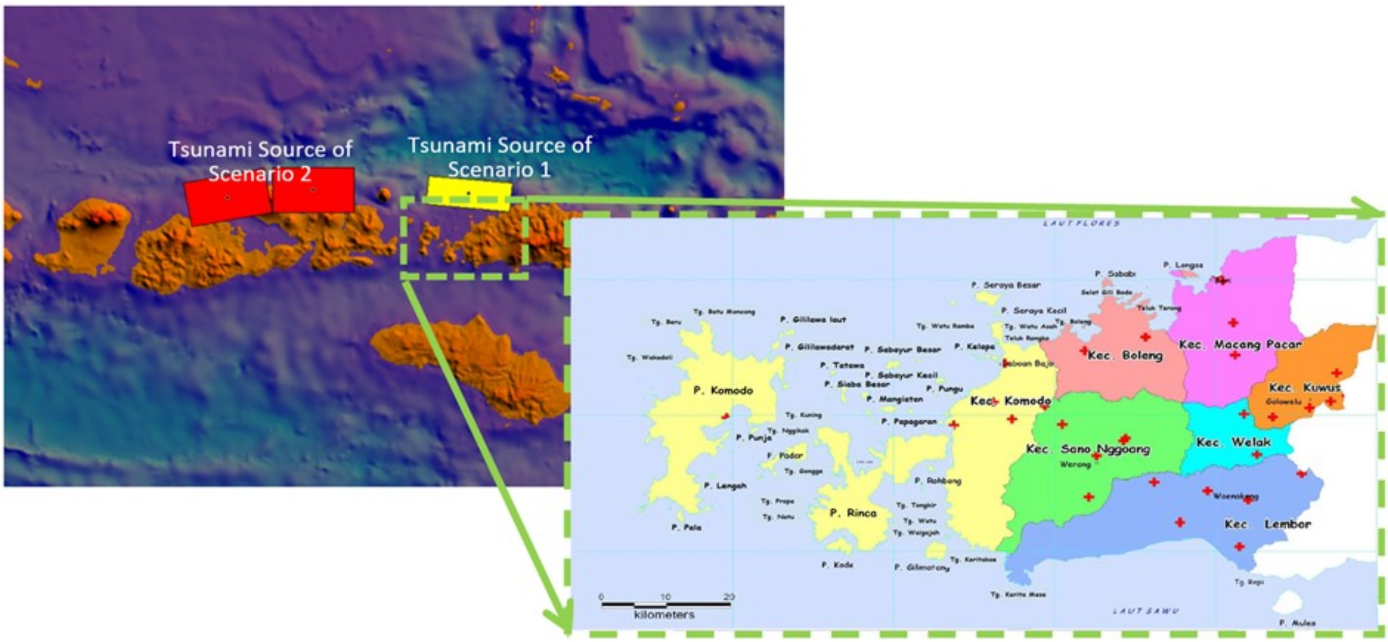


Figure 3. Domain and Scenario Source Earthquake and Tsunami Generator and the focus of the study location around Labuan Bajo (dotted box)

Table 1. Parameters of tsunami generating earthquake sources

Scenario	Scenario 1	Scenario 2	
Earthquake Source Segment	Flores Back-Arc Thrust West NT	Flores Back-Arc Thrust Sumbawa	
Magnitude (Mw)	7.5	8	
Longitude (°)	119,852	117.625	118.418
Latitude (°)	-8,152	-8,191	-8,119
Depth (km)	26	26	26
Strike (°)	95	80	90
Dip (°)	35	35	35
Slips (°)	90	90	90
Length (km)	85	83	83
Width (km)	29	46	46
Dislocation (m)	9	16.5	16.5

Prepare Input Data and Setup Model

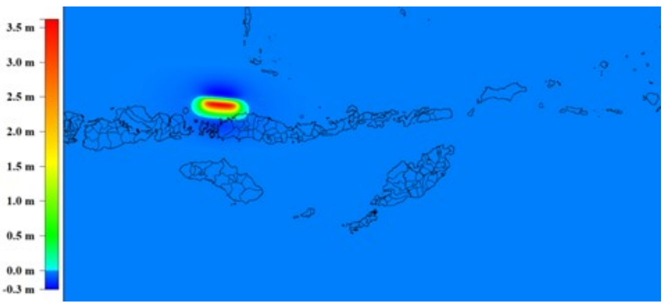
In this study, bathymetric data from "The General Bathymetric Chart of the Oceans (GEBCO)" with a resolution of ± 925 m (BODC, 2018) was used. The dimension of the domain model is 1818 columns and 823 rows with a resolution of 0.5' arc (925 m) and dt: 1 second. The tsunami wave height threshold of 0.05 m was stimulated for 2 hours, and the results were printed every 60 seconds.

3. Result and Discussion

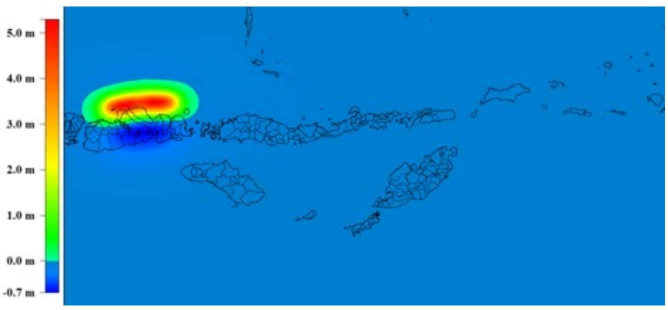
Initial Wave Height

The initial wave height of the tsunami generator due to the earthquake was obtained from the multi-deform model by inputting the nine parameters in Table 1.

Based on the multi-deform model for scenario 1, the maximum and minimum initial wave height of tsunami at the earthquake's epicentre are 3.619 m and -0.272 m, respectively (Figure 4a). For scenario 2, the maximum and minimum initial wave heights are around 5.297 and -0.695 m (Figure 4. b).



(a) Scenario 1



(b) Scenario 2

Figure 4. Initial Wave Height at the Source of the Tsunami Generating Earthquake

Potensial Tsunami Hazard Around Labuan Bajo

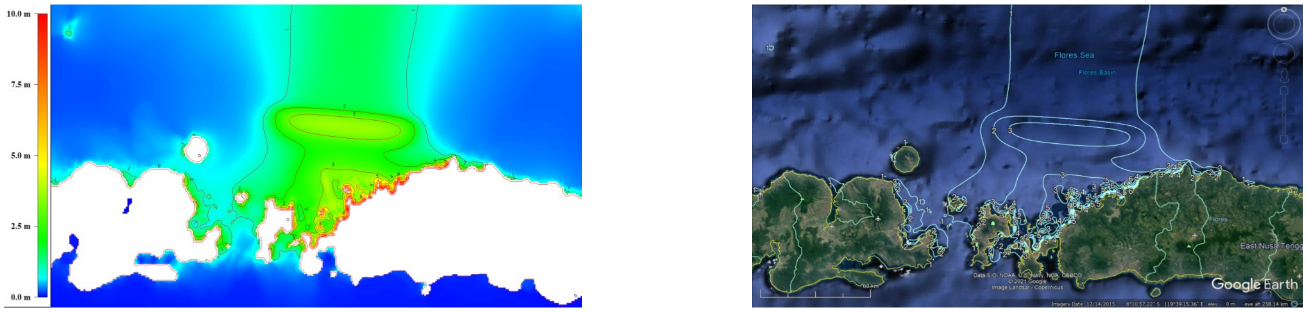
Simulation Result of Scenario 1

The simulation results from scenario 1 show that around Labuan Bajo, the maximum tsunami wave height is approximately 9 m (Figure 5). In general, along the coasts of Labuan Bajo, Tanjung Watu Asah, Rangka Bay, Boleng Bay, Terang Bay and Gili Bodo Strait it reach more than 5 m. At some specific locations, such as narrow bays and straits, where tsunami wave height amplifies, the maximum attained is 8-9 m (Patton, Wilson, Dengler, LaDuke, & Miller, 2019; Roger & Gunnell, 2012; UNESCO-IOC, 2007). This happened in small bays north of Labuan Bajo City, Rangka Bay, Teluk Terang and in the Gili Bodo Strait. The maximum height of tsunami waves in Rinca and Komodo Island, which occur in the northeastern part of Flores Island and adjacent to Gili Lawadarat Island, had reached approximately 7 and 8 m, respectively. A reasonably large tsunami wave height of 6 m also occurred on Sabayur Besar Island. Using the Probabilistic Tsunami Hazard Assessments (PTHA) method, it is known that in Labuan Bajo City, the probability of a tsunami with a wave height of more than 3 m is only 0.2%, with an average return period of about 530 years (Horspool et al., 2014, 2013). Horsopol et al. (2013) stated that the potential height on the Nusa Tenggara coast was 1.27, 2.84, 5.63 m for a return period of 100, 500, and 2500 years, respectively. The simulation model results show some similarities, especially for tsunami events that occur periodically every 2500 years.

The simulation results of scenario 1 show that the tsunami waves' arrival time is very fast, which is less than 2.5 minutes (Figure 6). This is because the source of the earthquake-tsunami generation in this segment is very close to the Labuan Bajo by less than 40km. Even in the eastern part, including Sababi and Longos Islands, the distance is only about 20 km (Handayani, 2008).

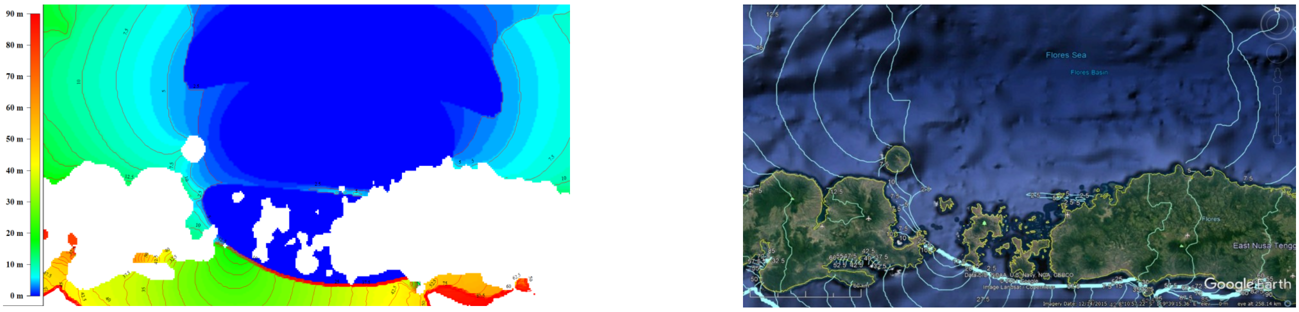
Simulation Results of Scenario 2

The simulation results of scenario 2 show that around Labuan Bajo, the maximum tsunami wave height reaches about 4 m (Figure 7). At the coast of Labuan Bajo, Tanjung Watu Asah, Rangka Bay, Boleng Bay, Terang Bay and Gili Bodo Strait, the wave height is less than 3 m. In particular locations, such as bays and narrow straits, the maximum height of tsunami waves is approximately 3 m. This happened in small bays north of Labuan Bajo City, Rangka



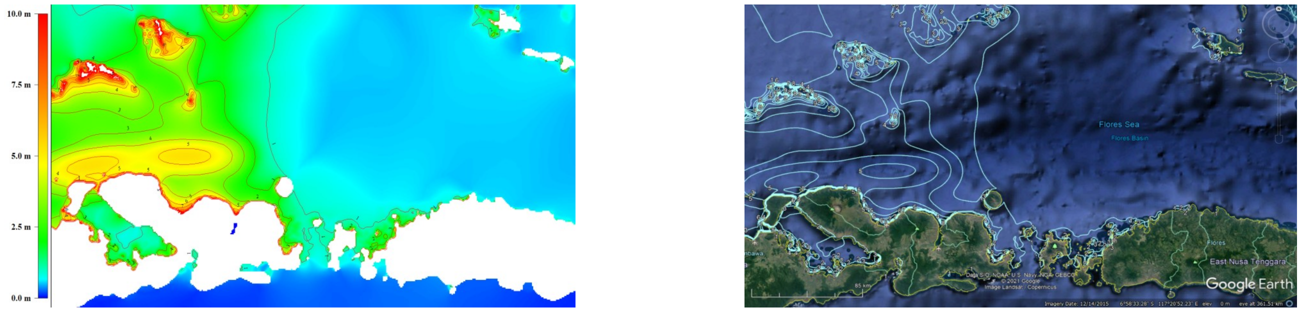
(a) (b)

Figure 5. Maximum Tsunami Height (meters) Scenario 1 Simulation Results (a) Model Simulation Results (b) Contours overlaid



(a) (b)

Figure 6. Tsunami Arrival Time (minutes) Scenario 1 Simulation Results (a) Model Simulation Results (b) Contours overlaid on Google Earth



(a) (b)

Figure 7. Maximum Tsunami Height (meters) Scenario 2 Simulation Results (a) Model Simulation Results (b) Contours overlaid on Google Earth

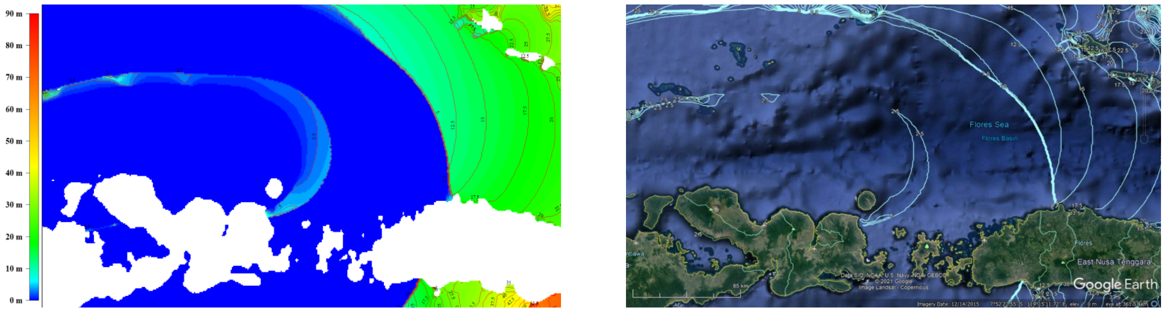
Bay, Teluk Terang and in the Gili Bodo Strait. The maximum height of tsunami waves in the Rinca and Komodo Islands, which occur in the northeast as well as adjacent to Gili Lawadarat, has reached 3 and 5 m, respectively. A fairly large tsunami wave height of 5 m also occurred on Sabayur Besar Island.

The simulation results of scenario 2 show that the tsunami waves' arrival time is very fast, which is less than 2.5 minutes (see Figure 8). The source of the tsunami is very close to Labuan Bajo, and the earthquake magnitude is quite large; hence, its wave propagation is very prone to reach the area and its surroundings.

The maximum height and estimated arrival time of the tsunami at the coast were determined by performing extraction along the coastline on the north side. The graph in Figure 9 shows the maximum wave height and estimated tsunami arrival time along the coastline, both the results of modeling scenarios 1 and 2.

The results of the Flores tsunami (1992) stimulated by Imamura show that the coastline east of Maumere (a city on Flores island) had a maximum predicted height of 1.4 m at the north shore of the Hading Bay, where the first wave arrived at the coastline within 5 minutes (Yeh et al., 1993). Using the 1992 Flores earthquake parameter, which is placed perpendicular to the research area, the maximum and minimum tsunami heights were obtained to be around 4-5 and 0.2 m at Sowa and Kolo, near the mouth of Bima Bay, as well as Kalaki at the inner bay, respectively (Yudhicara & Robiana, 2016).

The tsunami arrival time in Labuan Baco is much faster compared to other locations, such as the 2004 tsunami that began flooding mainland Aceh in 15-20 minutes, the leading edge of the 2006 tsunami, which took 40-60 minutes to



(a) (b)

Figure 8. Tsunami Arrival Time Contour (minutes) (a) Model Simulation Results (b) Contours are overlaid on Google Earth

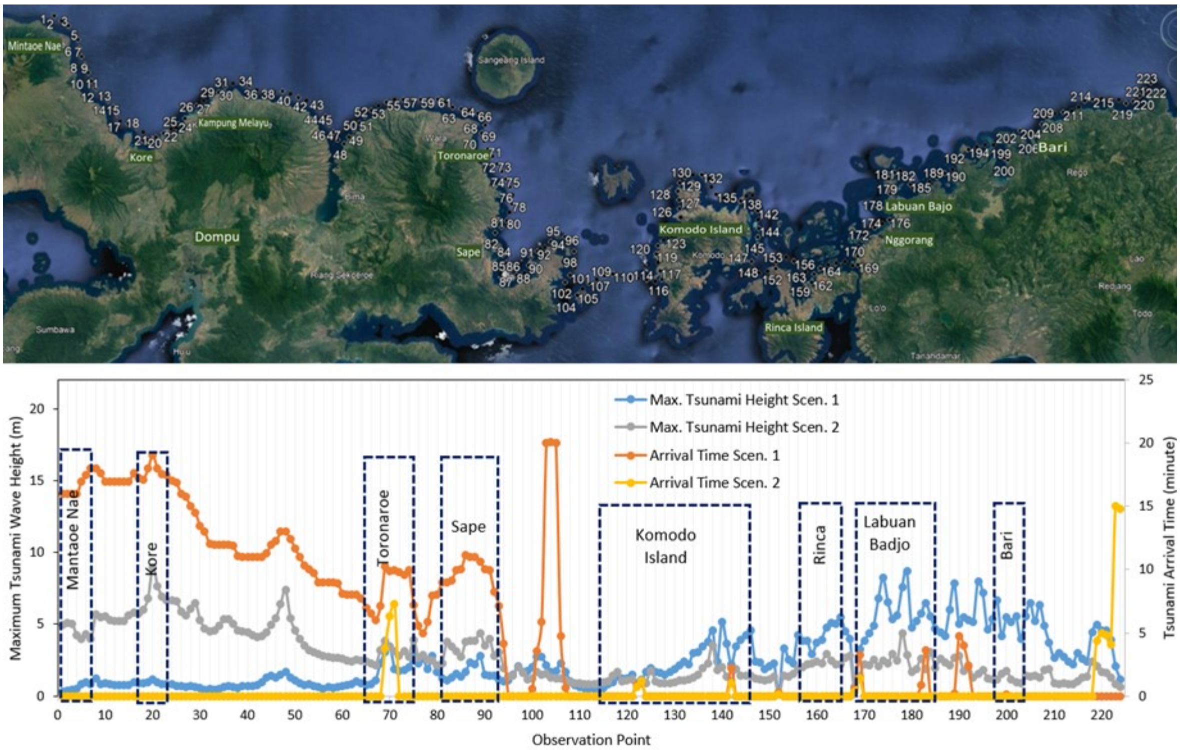


Figure 9. Maximum and Arrival Time of Tsunami Wave at Observation Point

travel from its source to the south coast of Java (Pangandaran)((Yulianto, Kusmayanto, Supriyatna, & Dirhamsyah, 2009). In Palu, the wave reached the bay mouth in 10 minutes and arrived at the coast of the study area in 20 minutes (Alam et al., 2021). Meanwhile, the height remains in the same range. For example, the simulation result of the tsunami at Pangandaran Bay (2006) shows a wave height of approximately 2-9 meters (Subardjo, Saputro, & Aeda, 2017), whereas, at tsunami Palu (2018), the highest peak of water level on the coast occurred in the second wave with an amplitude and wave height of 2.45 m as well as 5.19 m, respectively (Alam et al., 2021).

In the Tohuku tsunami (2011), the initial wave entered Sendai Bay around 38 minutes with a wave height of 3-8 m (Yamazaki, Cheung, & Lay, 2013). The tsunami in Chile (September 16, 2015) reached the closest coastal villages in less than 12 minutes (Aránguiz et al., 2016). Gegar et al. simulated a potential tsunami in Whitianga-Mercury Bay, New Zealand, due to an earthquake from the Kermadec Trench. It was stated that the first waves penetrate Mercury Bay within 75–98 minutes after the fault rupture and take 11–18 minutes arrival time at the Whitianga foreshore (Prasetya, Healy, & de Lange, 2011)

Tsunami Disaster Mitigation in Labuan Bajo Towards a Disaster-Resilient Tourist Area

The determination of the Labuan Bajo area as a super-priority tourist area is expected to become "New Bali", leading to the arrival of more tourists, mainly foreign. In addition, this area is very close to Komodo Island, which in 2012 was designated as one of the "new seven wonders of nature" by the New Seven Wonders Foundation (New 7 Wonders of Nature, 2012). Therefore, the Labuan Bajo area and its surroundings are receiving increasing international attention. In 2021, the number of foreign tourists to Labuan Bajo was approximately 250,000, and in 2022 it is targeted at 500,000 (Ardiansyah, 2021). Based on the foregoing, the international community needs complete information about the tourist area of Labuan Bajo. So, in addition to information about tourism, information about disaster vulnerability (including tsunami) is also needed.

The arrival time of the tsunami at Labuan Bajo and its surroundings is very fast; hence, there is a need for anticipatory action from the start. According to Indonesian tsunami expert Widjo Kongko, no technology can predict when, where, and how big a tsunami-generating earthquake will occur (Pranita, 2021). Therefore, the Agency for Meteorology, Climatology, and Geophysics (BMKG) is currently coordinating the InaTEWS Indonesia Early Warning System (Presiden Republik Indonesia, 2019). The arrival time of the tsunami in Labuan Bajo was very fast, while the early warning from BMKG took 5 minutes after the earthquake (BMKG, 2013). For this reason, awareness and preparedness of all stakeholders, including the community, is necessary. One of the essential steps is "using local, indigenous and traditional knowledge, wisdom, experiences, and practices, as appropriate, to complement scientific knowledge in disaster risk assessment and the development and implementation of policies, strategies, plans, and programs" (UNISDR, 2015). Traditional, indigenous and local knowledge, wisdom, and experiences have saved many lives during the occurrence of disasters, such as the story about "Nepar" (turtle), scream "Ami Norang:, and spiritual intelligence in Tana Ai-East Nusa Tenggara (Ignasius Angin, 2019; Kusuma, Ramadhan, 'Aini, & Suryanda, 2020; Thene, 2016). Other local knowledge that can be used is when the earth shakes, the seawater recedes far into the open sea, the water roars, a lot of fish strande and the animals run away, resulting in the movement to higher heights (Yulianto, Kusmayanto, Supriyatna, & Dirhamsyah, 2010).

Another aspect of preparedness is spatial planning in tsunami-prone areas. In planning the development of disaster-responsible tourism areas, the "6A components, namely attractions, accessibility, amenities, available packages, activities, ancillary services", need to be considered alongside threats, vulnerabilities, capacities, and disaster risks (Khaerani L & Rahayu, 2020; Pahleviannur, Wulandari, Sochiba, & Santoso, 2020).

"Disaster management is a dynamic, integrated, and sustainable process of improving the quality of steps related to a series of activities, including prevention, mitigation, preparedness, emergency response, evacuation, rehabilitation, and reconstruction" (Jokowinarno, 2011). Therefore, spatial planning for disaster risk reduction is the first and primary step in developing an area or region (like tourism in tsunami-prone areas) (Prawiranegara, 2020).

In Indonesia, tourism in coastal areas is a disaster-prone industry and involves many stakeholders (Wulung & Abdullah, 2020). Therefore, risk management should involve all parties, such as tourism destination managers, government, industry players, academics, tourism associations, and integrated local communities. In the context of tourism, the area managers (including BPOLBF) have two roles in disaster risk management: working partners with the government and coordinators for other stakeholders in handling disaster management systems coordinated according to procedures and plans (Wulung & Abdullah, 2020).

BPOLBF as a tourism area manager, can undertake efforts to mitigate tsunami disasters by conducting the following functions (Wulung & Abdullah, 2020):

Cooperation with BMKG regarding early warning systems and equipment.

a. Provision of mustering points and evacuation routes
b. Plan the breakwater infrastructure
c. Evaluate the layout of the building by existing standards
d. Provide training for all existing tourism human resources
e. Deliver socialization related to disaster mitigation for visiting tourists
f. Plan and build shelters in hilly areas

The provincial and district tourism offices can synergistically integrate development and disaster mitigation. This is performed through socialization with business actors such as hotels, restaurants, villas, and shops along the waterfront area. Prepare all community components in existing tourist areas to face the tsunami holistically and cooperate with all parties in development and preparation to obtain maximum results. Currently, the government of West Manggarai Regency, with the Director-General of Human Settlements (Ministry of Public Works), is developing a residential area supported by the concept of disaster mitigation, especially the tsunami in Labuan Bajo (Dirjen Cipta Karya, 2013). Furthermore, roads and sidewalks have been built along the coast and local planting of Sakura flowers and Flamboyan trees to reduce the impact of the tsunami (Kementerian PUPR, 2021).

4. Conclusion

It was concluded that the Flores back-arc thrust earthquake caused a fairly high tsunami and very fast arrival time at Labuan Bajo. Its wave height on the coast of Labuan Bajo, Rinca Island, and Komodo Island is at least 3 m. Under certain earthquake conditions and morphology, the tsunami wave height reaches 8-9 m. In general, the arrival time of tsunami waves on the coast of Labuan Bajo and its surroundings is less than 2.5 minutes. Therefore, it is necessary to create awareness and preparedness for all stakeholders, including the community. The synergy between BPOLBF, BNPB, BPBDs, the Ministry of Tourism, the Local Government Tourism Office, the industry, and society is essential to mitigate the tsunami, making Labuan Bajo a resilient tourism area.

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