Tsunami Hazard Potential Modeling as Tourism Development Considerations in the North of Lombok Strait

M Wibowo¹, W Kongko², W Hendriyono¹, and S Karima¹

¹ Center of Technology for Maritime Industrial Engineering (PTRIM), BPPT, Indonesia
² Laboratory for Harbour Infrastructure and Coastal Dynamics Technology (BTIPDP), BPPT, Indonesia
Corresponding author’s: mardi.wibowo@bppt.go.id

Abstract. Currently, the central government and provincial governments of Bali and West Nusa Tenggara are promoting tourism development in North Bali and North Lombok. In the development of tourism, besides consider the potential of existing tourism objects, the economy, and its supporting facilities, the potential threats of disasters must also be considered. Based on historical records, one of the potential disasters in northern Bali and Lombok is a tsunami. This study aims to determine the height and the arrival time of the tsunami along the northern coasts of Bali and Lombok. This study was carried out by simulation and numerical modeling, using the TUNAMI Model. Modeling was carried out for 2 hypothetical scenarios caused by an earthquake from the Flores Back-arc Thrust. Based on this model, it is known that the height of tsunami on Trawangan Island is +6 m with an arrival time of ±3 minutes, while on the north coast of Bali the height of the tsunami is +0.6 m with an arrival time of ±21 minutes. The arrival times of the tsunami on the north coast of Bali and Lombok are so fast.

1. Introduction

1.1. Background
The Lombok strait separates the islands of Bali and Lombok. Tourism in Bali and Lombok is not only famous domestically but also abroad, and the north side of Bali and Lombok islands has a lot of tourism objects that can be potentially developed. At present, there is an unequal development of tourism in the northern part of Bali when compared to the southern part, in the way that North Bali is far behind compared to South Bali [1][2]. Whereas there is a lot of potential for natural, cultural, and historical tourism objects in North Bali which is interesting is not inferior to South Bali [1][2]. Karangasem Regency is one of the coastal areas in Bali which has great potential for the development of marine tourism since it has various ecosystems such as white sand, beautiful corals, unspoiled nature, and fish [3]. Apart from spiritual tourism (Pura Besakih) which is already very well known, one of the marine tourism potentials being developed in North Bali is Tulamben and Jemeluk Beach in Karangasem Regency [4], and Virgin Beach in Baubau Village [3]. Currently, to support tourism development in North Bali, the Central Government plans to build North Bali International Airport and the Bali-North-South highway axis connecting Denpasar and Buleleng [5]. On the east side of the Lombok Strait is Lombok Island which was selected as the winner of the World Travel Halal Summit award in Abu Dhabi, United Arab Emirates [6]. The Senggigi-Tiga Gili area in North Lombok is designated as one of the Regional Strategic Tourism Areas (KSPD) in West Nusa...
Tenggara Province, based on the West Nusa Tenggara Provincial Regulation No. 7, 2013 [7]. This area is so popular among tourists, owing to its ease of access and supporting infrastructures [6].

In the development of tourism, in addition to considering the potential of existing tourism objects, the economy, and its supporting facilities, consideration must also be given to the potential threats of disasters that may occur. National Law No. 26 of 2007 on Spatial Planning mandates that since Indonesia lies in a disaster area, spatial planning must be based on disaster mitigation [8], including spatial planning for the development of tourist areas in North Bali and North Lombok. Regulation of the Minister of Agrarian and Spatial Planning/Head of the National Land Agency No. 1 of 2018 concerning Guidelines for the Preparation of Provincial/District/City Land-use planning (RTRW) states that the designation of coastal boundary protected areas must include and consider tsunami-prone areas [9].

Based on historical records, one of the potential disasters that threaten North Bali and North Lombok is the tsunami. Based on data and references, there have been several tsunamis in North Bali and North Lombok regions, due to tectonic earthquakes and volcanic eruptions. Based on data from the Earthquake and Tsunami Center-BMKG [10] since 1815 until now, there have been at least 6 tsunamis in northern Bali and Lombok (the Bali Sea and the Flores Sea). These tsunamis occurred in 1815, 1816, 1818, 1857, and twice in 1917. The largest tsunami occurred in 1815 which resulted in 1200 deaths [10][11]. The tsunami incident data was also strengthened by data in the Windows International Tsunami Database [12]. Based on BMKG records, several earthquakes have hit Bali. Among them was an earthquake in 1816 called Gejer Bali which killed at least 1500 people. According to Earthquake and Tsunami Centers-BMKG, this earthquake also generated a tsunami wave that crashed along the coasts of Karangasem and Buleleng [10][13].

Currently, assessments of tsunami potential in northern Bali and Lombok are still rarely conducted, while most of the tsunami studies are conducted in southern Bali and Lombok which originate from the Subduction Zone between the Indo-Australian Plate and the Eurasian Plate. According to [14] based on the results of an analysis of the impact of the tsunami inundation using the amount of infrastructure, the Benoa Bay area - Badung Regency is a high-risk area for tsunami hazards. Based on a probabilistic analysis of the Bali Island tsunami hazard, with the sources of Java subduction (a combination of Java and Sumba) and the Flores fault, it is known that within 100 years the tsunami amplitude that may occur at a depth of 30 m in the southern waters of Bali Island ranges from 2 to 4 meters. Based on the value of seismicity, tsunami-prone areas are the southern regions of Bali, Karangasem, and Buleleng [15]. Tsunami mapping in Bali using the TOAST application has shown that tsunami-prone areas in Bali are Kuta Beach, East Buleleng, and Karangasem [15]. DLR/GTZ has prepared a multi-scenario tsunami hazard map for South Bali at a scale of 1: 25,000 [16].

Based on the description above, it is very necessary to have tsunami modeling in the north of Bali and Lombok. This modeling aims to determine the heights and arrival times of the tsunami waves based on multi hypothetical scenarios along the north coast of Bali and Lombok. The results of this modeling are expected to be useful as consideration for regional development in the northern region of Bali and Lombok.

This tsunami potential study was carried out using numerical modeling of tsunami waves due to tectonic earthquakes in Flores backarc thrust using the TUNAMI Model. This model has been widely used to model tsunamis in various locations with fairly good validity results. To find out the validity of this TUNAMI model, Rahmawan has used this model for the Pangandaran tsunami event on July 17, 2006, where the results (of this model with TUNAMI) have similarities with the results of the BMKG survey [17]. The average difference between the simulated wave height and the BMKG survey results is around 0.98 m (20.74%) [17]. Mardi et al state that the TUNAMI, TUNA, COMCOT, MOST and ANN Tsunami Forecast models have been used quite well to simulate tsunamis based on the Sumatra-Andaman tsunami event [18]. Adriano et al also used TUNAMI to model the tsunami on the coast of Sendai-Japan that occurred on 22 November 2016 with two earthquake source models [19]. The results of the model were then validated with field observation data and obtained NRMSE values of 0.686 - 0.863 [19]. This TUNAMI model is also used to simulate tsunami in southern Java with very good results [20][21].
1.2. Location of Study
The study area focuses on the Lombok Strait, especially on the north side which is still lacking tsunami-related studies (see figure 1).

![Figure 1. Location of study](image)

1.3. Tectonic Pattern in North Bali and Lombok
Based on seismic and tectonic characteristics, and supported by existing geophysical data characteristics of the islands of Bali and Lombok, the earthquake sources that affect the tsunami are the subduction zone in the south of Bali-Lombok and the back-arc thrust fault in the north of Bali and Lombok. Earthquakes that occur in the Bali-Lombok subduction zone are generally separated into two groups, namely the megathrust earthquake which is an earthquake due to shallow intrusion, and the Benioff Zone earthquake which is an earthquake due to deep intrusion [22].

According to [23], there are four earthquake sources around the island of Bali, namely the Java subduction earthquake, the Sumba subduction earthquake, the Flores fault earthquake, and the Sumba fault earthquake. Based on the Earthquake Source and Hazard Map of Indonesia, active faults that are identified based on the earthquake and available publications show the characteristics of reverse thrust behind the archipelago and in front of the arc. Besides, according to the National Earthquake Study Center of Indonesia, there are also fundamental faults that traverse north-south to northeast-southwest [24].

![Figure 2. Map of potential earthquake sources in Bali, Nusa Tenggara, and the Banda Sea, the potential earthquake source at the north of Bali and Lombok is showed blue rectangle](image)

Based on the Earthquake Source and Hazard Map of Indonesia, in the north of Bali and Lombok, there is a potential earthquake originating from the Flores back-arc thrust (both Bali and Lombok-
Sumbawa segments), like the Lombok earthquake that occurred in 2018 [25]. The potential magnitude of the earthquake from the Flores backarc thrust Bali segment is M7.4 with a movement of 6.95 mm/year, while that of the Lombok Sumbawa segment is M8.0 with a movement of 9.9 mm/year (see figure 2) [24].

2. Methodology

2.1. The TUNAMI Model

The numerical model used in this study is the TUNAMI F1 Model developed by Imamura from Tohoku University. TUNAMI stands for Tohoku University's Numerical Analysis Model for Investigation. TUNAMI F1 is a tool for modeling wave propagation in the sea-based on linear equations at spherical coordinates. TUNAMI F1 does not take into account non-linear terms such as bottom roughness. The estimated impact of tsunami propagation can be quantified using numerical modeling. The assumption used in this numerical modeling is that tsunami waves propagate in the form of long waves (wave height is much smaller than the wavelength), water particles do not have vertical acceleration and water pressure is equal to the pressure due to gravity. Several basic equations and approaches are used to model tsunamis. These equations are based on the principle of conservation of mass applied to incompressible fluids [26] [27]. These equations can be simply written as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$  \hspace{1cm} (1)

where:

$M = \int_{-h}^{h} u dz = \bar{u} (h + \eta)$ \hspace{0.5cm} (water discharge/flux in x-direction)

$N = \int_{-h}^{h} v dz = v (h + \eta)$ \hspace{0.5cm} (water discharge/flux in y-direction)

Momentum equation in X direction:

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{D} \right) + gD \frac{\partial \eta}{\partial x} + \frac{g \eta^2}{D^{7/3}} M \sqrt{M^2 + N^2} = 0$$  \hspace{1cm} (2)

Momentum equation in Y direction:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{MN}{D} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + \frac{g \eta^2}{D^{7/3}} N \sqrt{M^2 + N^2} = 0$$  \hspace{1cm} (3)

where:

$M = \int_{-h}^{h} u dz = \text{debit in x-direction (m}^2/\text{s})$

$N = \int_{-h}^{h} v dz = \text{debit in y-direction (m}^2/\text{s})$

$D = (h + \eta)$ = total instantaneous water depth (m)

$h$ = water depth from sea-bottom to the mean sea level (m)

$\eta$ = instantaneous water height (elevation) from the surface (m)

$g$ = gravitational acceleration (m/s$^2$)

$n$ = roughness coefficient (manning roughness)

$t$ = time (s)

Tsunami modeling requires a wave input based on the determination of the fault parameters. Fault parameters such as length (L) and fault width (W), energy and magnitude, epicenter depth (H), slip (D) and focal mechanism (strike (\(\theta\)), dip (\(\delta\)) and slip angle (\(\gamma\) )) are the main parameters of the earthquake, which determine the initial formation of a tsunami wave before it propagates [27] [28].

2.2. Modeling Scenarios

The scenarios used in this modeling are hypothetical scenarios based on the potential for the biggest earthquake that might occur. There are two tsunami modeling scenarios in the north of Bali and Lombok. The first scenario is due to the Flores back-arc thrust earthquake from the Bali segment,
and the second scenario is due to an earthquake from the Lombok-Sumbawa segment. The potential earthquake magnitude from the Flores backarc thrust Bali segment is M7.4 with a movement of 6.95 mm/year, while that of the Lombok Sumbawa segment is M8.0 with a movement of 9.9 mm/year (see figure 3) [24]. Based on the 1900-2020 earthquake data from the USGS, the fault of the source of the earthquake in northern Bali and Lombok has a depth of 9 - 40 km (mean depth of 27 km), strike 79 - 127° (average strike of 85°) and dip 15 - 46° (an average dip of 30°). The fault dimension (L x W) is calculated based on an empirical study conducted by Wells & Coppersmith for reverse thrust, with values of parameters as shown in table 1 [28].

| Scenario | Scenario-1 | Scenario-2 |
|----------|------------|------------|
| **Source** | Flores Backarc Thrust Bali segment | Flores Backarc Thrust-Lombok Sumbawa segment |
| **Magnitude** | 7.4 | 8.0 |
| **Lon (°)** | 115.95 | 117.625 |
| **Lat (°)** | -8.05 | -8.191 |
| **Depth (km)** | 27.00 | 26 |
| **Strike (°)** | 93.00 | 80 |
| **Dip (°)** | 27.00 | 35 |
| **Slip (°)** | 90.00 | 90 |
| **L (km)** | 75.00 | 83 |
| **W (km)** | 27.00 | 46 |
| **d (m)** | 2.70 | 16.5 |

2.3. Geometrical Data, Fault Segmentation, and Model Setup
The bathymetry data used are gathered from National Bathymetry data (BATNAS) with a resolution of 6 arcsec (180 m) [29]. The model domain consists of 1931 columns and 796 rows with an equal spatial interval (dx and dy) of 12 arcsec (360 m) and time step (dt) of 0.5 seconds. The simulated time is 2 hours (7200 seconds), while the threshold height i.e. the height when the wave is considered to be a tsunami, is 0.5 m and. Simulation results are stored every 1 minute. The fault segmentation as the earthquake and tsunami generator is calculated based on the location (epicenter) and magnitude of the earthquake using the theory of Wells & Coppersmith [28] (see explanation in section 2.2). The computational domain and fault segmentation as the source of the earthquake and tsunami are shown in figure 3 below.

![Figure 3. Domain and segmentation of earthquake or tsunami sources in the north of Bali-Lombok](image-url)
2.4. Research Activity Stages
The sequence of activities for the studies and modeling of potential tsunamis in northern Bali and Lombok is as follows:
   a. Collection and desk-study of secondary data and previous research.
   b. Development of potential tsunami scenarios to be modeled.
   c. Pre-processing, such as preparing the model domain by interpolating existing data according to a set resolution, and also preparing locations of the tsunami observation points.
   d. Generation of tsunami initial waves at the earthquake location (source) using a “Multideform Model” involving 9 parameters in table 1 for each predetermined scenario [27].
   e. Setup and running the TUNAMI F1 model.
   f. Postprocessing and data analysis of modeling results.

3. Results and Discussion

3.1. Initial Wave Height
The initial wave height of the tsunami sources for scenarios 1 and 2 are obtained from the “Multideform Model” run using 9 parameters.

Based on the results of the “Multideform Model” runway for scenario 1, the maximum height of the initial tsunami waves at the earthquake source is about 0.59 m and the minimum is about 0.12 m (figure 4.a). For scenario 2, the maximum height of the tsunami source reaches more than 5 m and the minimum height is -0.7 m (figure 4.b).

![Figure 4](image)

(a) Initial tsunami wave at the source (earthquake) for scenario 1; b. Initial tsunami wave at the source (earthquake) for scenario 2

3.2. Scenario 1 Model Results
From the results of the Tunami F1 model, data on the arrival times and heights of the tsunami waves at predetermined observation points are obtained.

The maximum wave heights of the simulation model scenario 1 are shown in figure 5(a) and 5(b). These figures show that the maximum wave height at Karangasem beach is around 0.5 m, Denpasar
1.0 m, Mataram 1.5 m, and the highest wave occurs in the waters between the island of Gili Air and Lombok which reaches about 5 m.

![Figure 5](image1.png)

**Figure 5.** Model results from scenario 1, a. Contours (isolines) of maximum tsunami wave heights; b. Maximum tsunami wave heights at important locations in Lombok Strait

The high tsunami waves in the waters between the islands of Trawangan, apart from being very close to and directly facing the tsunami source, is also due to the shallow water depth and the shape of the narrow strait. The shallow and narrow water causes the amplification of the tsunami wave height [30].

The fastest arrival times of the tsunami waves occur at Karangasem beach and the north coast of Lombok, which was about 1 minute after the earthquake occurred (see figures 6(a) and 6(b)). Tsunami arrival times in Denpasar and Mataram are about 25 and 9 minutes respectively, while in Gili Trawangan tsunami arrives just 3 minutes after the earthquake.

![Figure 6](image2.png)

**Figure 6.** Model results from scenario 1, a. Contours (isolines) of tsunami arrival times (in minutes); b. Tsunami arrival times at important locations in Lombok Strait

### 3.3. Scenario 2 Model Results

The maximum wave height of the simulation model scenario 2 is shown in figure 7(a) and 7(b). From these figures, the maximum wave height at Karangasem beach is + 0.6 m, Denpasar + 1.5 m, West Lombok + 2.8 m, and the highest wave occurs in the waters between Gili Air and Lombok islands which reaches + 6.5 m. The high tsunami waves in the waters between the islands of Trawangan, apart from being very close to and directly facing the tsunami source, is also due to the shallow water depth and the shape of the narrow strait.

The fastest arrival times of the tsunami waves occur at Karangasem beach which is about 21 minutes, and Gili Trawangan at about 16 minutes after the earthquake occurs (see figure 8(a) and 8(b)). Tsunami arrival times in Denpasar and Mataram are about 40 and 22 minutes respectively.
3.4. Development of Tourism in Tsunami Prone Areas

Based on the modeling, it is shown that the arrival times of the tsunami in northern Bali and Lombok are so fast that anticipatory actions are needed. The main consideration in developing cultivated areas including tourism in tsunami-prone regions is the principle of disaster risk reduction through spatial planning [31]. This principle consists of 4 things, namely:

a. Reducing the level of hazard by creating the coastal boundary space in the form of mangroves, sea cypresses, ketapang, waru, sand dunes, or building barriers and breakwaters in front of the tourist area to be developed

b. Reducing exposure by designating open spaces in tsunami-prone areas as buffer zones, such as parks, agriculture, sports, or recreation.

c. Reducing vulnerability of the area by adaptation efforts, for example by tightening licensing requirements and zone allocation.

d. Increasing capacity, where buildings with 3 floors or more are required to provide vertical evacuation routes and spaces with a building structure that can withstand tsunami and earthquake forces, development of a tsunami evacuation system, development of an early warning system, raising public awareness by installing tsunami-prone posters at tourist sites, inducing safety measures for visitors, forming disaster response groups at tourist sites, etc. Besides, it is necessary to provide education because it is proven to be very effective in improving community awareness and preparedness [32].

This principle can be implemented effectively if it is carried out in an integrated manner by involving all existing stakeholders. According to BPBD NTB, these 4 principles have been implemented in West Nusa Tenggara, especially in the 3 Gili area (Gili Trawangan, Meno, and Gili Air) [33].
4. Conclusions

Based on history and existing earthquake maps, the north coasts of Bali and Lombok are prone to tsunami disasters. Scenario 1 shows that the highest waves occur around the Gili area (+5 m) with arrival time at about 3 minutes, while in the city of Denpasar the wave is about +1 m and the arrival time is about 25 minutes. Scenario 2 shows the highest wave also occurs around the Gili area (+6.5 m) with an arrival time of about 16 minutes, while in Denpasar the wave height is ±1.5 m and the arrival time is around 40 minutes.

The arrival times of the tsunami waves on the north coasts of Bali and Lombok are so fast, therefore it is necessary to include anticipatory actions in the development of tourism, such as spatial planning based on disaster mitigation. Mitigation measures that can be taken are building a wave barrier (hard or soft structures), a tsunami early warning system, evacuation routes, evacuation sites, and so on. Further studies are needed to determine the effectiveness of evacuation routes, evacuation sites, and infrastructure designs that will be and have been built. Besides, it is necessary to provide education to increase community awareness and preparedness.

References

[1] Marsitadewi K E 2014 Strategi Pengembangan Pantai Lovina Sebagai Destinasi Pariwisata Unggulan di Kabupaten Buleleng (Gadjah Mada University)
[2] Hersaputri L D 2017 Arahan Pengembangan Pariwisata dalam rangka Mengurangi Ketidakmerataan Pariwisata Studi Kasus Kabupaten Badung dan Gianyar Jurnal Teknik ITS C 459–62
[3] Darnita I K, Puspa I A T and Widana I K A 2018 Pengembangan Virgin Beach Sebagai Daya Tarik Wisata Bahari di Desa Bugbug Karangasem Jurnal Penelitian Agama Hindu 2 479–83
[4] Hidayah A, Sunarti S and Hakim L 2017 Potensi Dan Pengembangan Objek Wisata Bahari Tulamben, Kabupaten Karangasem, Bali Jurnal Administrasi Bisnis S1 Universitas Brawijaya 50 94–8
[5] Wanto 2019 Membangun Bandara di Bali Utara agar Menjadi ”Tourism Transit or Hub” | Wisata Gatra Online
[6] Septiani E, Santoso B, Mulyadi and Muhdin 2019 Analisis Preferensi Pengunjung Kawasan Wisata Gili Meno Kabupaten Lombok Utara Jurnal Distribusi 7 141–54
[7] Pemerintah Nusa Tenggara Barat 2013 Peraturan Daerah Provinsi Nusa tenggara Barat No 7 tahun 2013 Tentang Rencana Induk Pembangunan Keparisivasaan Daerah Tahun 2013-2028 (Indonesia)
[8] Pemerintah Republik Indonesia 2007 Undang-Undang Republik Indonesia Nomor 26 Tahun 2007 tentang Penataan Ruang
[9] Kementerian Agraria dan Tata Ruang/ Kepala Badan Pertanahan Naisional 2018 Permen Agraria/Kepala BPN No. 1 Tahun 2018 tentang Pedoman Penyusunan Rencana Tata Ruang Wilayah Provinsi, Kabupaten Dan Kota ((Regulation of the Minister of Agrarian and Spatial Planning / Head of the National Land Agency No. 1 of 2018 concerning Guideline
[10] Triyono R, Prasetya T, Daryono, Anugerah S D, Sudrajat A, Setiyono U, Gunawan I, Priyobudi, Yatimantoro T and Hidayanti 2019 Katalog Tsunami Indonesia Tahun 416-2018 ed R Triyono, T Prasetya, Daryono, S D Anugerah, A Sudrajat, U Setiyono, I Gunawan, Priyobudi, T Yatimantoro and Hidayanti (Jakarta, Indonesia: Badan Meteorologi Klimatologi dan Geofisika)
[11] NOAA 2015 Global Historical Tsunami Database - World Data Service National Geophysical Data Center, NOAA Boulder, CO, USA
[12] WinITDB 2007 Integrated Tsunami Database for the World Ocean
[13] BMKG 2018 Katalog Gempa Signifikan dan Merusak 1874-2017 ed T Prasetya and Daryono (Jakarta: Pusat Gempa Bumi dan Tsunami BMKG)
[14] Pratama W P 2017 Pemetaan Bahaya Tsunami dan Dampaknya Terhadap Infrastruktur di Daerah Teluk Benoa Provinsi Bali (Universitas Brawijaya Malang)
[15] Baskara B, Sukarasa I K and Septiadhi A 2017 Pemetaan Bahaya Gempa Bumi Dan Potensi
Tsu-Nami Di Bali Berdasarkan Nilai Seismisitas Buletin Fisika 18 20

[16] DLR and GTZ 2010 Peta Bayahana Tsunami Bali (Denpasar)

[17] Rahmawan S H, Ibrahim G, Mustofa M A and Ahmad M 2012 Studi Potensi Bayahana Tsunami di Selatan Jawa (Bandung)

[18] Mardi N H, Malek M A, Liew M S and Lee H E 2015 A Conceptual Review of Tsunami Models Based on Sumatera-Andaman Tsunami Event IncIEC 2014 ed R Hassan (Singapore: Springer Science+Business Media Singapore 2015) pp 387–96

[19] Adriano B, Fujii Y and Koshimura S 2018 Tsunami source and inundation features around Sendai Coast, Japan, due to the November 22, 2016 M w 6.9 Fukushima earthquake Geoscience Letters 5 12

[20] Kongko W and Schlurmann T 2011 The Java tsunami model: Using highly-resolved data to model the past event and to estimate the future hazard Proceedings of the Coastal Engineering Conference pp 1–16

[21] Kongko W and Hidayat R 2014 Earthquake-Tsunami in South Jogjakarta Indonesia: Potential, Simulation Models, and Related Mitigation Efforts IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) 2 18–22

[22] Hamilton W 1979 Tectonics of the Indonesian Region Geological Society of Malaysia, Bulletin 6 3–10

[23] Irsyam M, Sengara W, Aldiamar F, Widyantoro S, Triyoso W, Natawidjaja D H and Kertapati E 2010 Ringkasan Hasil Studi Tim Revisi Peta Gempa Indonesia 2010 (Bandung)

[24] Pusat Studi Gempa Nasional 2017 Peta Sumber dan Bayahana Gempa Indonesia Tahun 2017 ed M Irsyam, S Widiyantoro, D H Natawidjaya, I Meilano and Dkk (Bandung: Puslitbang Perumahan dan Pemukiman)

[25] Natawidjaya D H, Widyantoro S, Meilano I, Hidayati S, Irsyam M and Daryono M 2018 Penjelasan Komprehensif Sumber Gempa Lombok Kajian Rangkaian Gempa Lombok Nusa Tenggara Barat ed I Masyhur, N R Hanifa and D Djarwadi (Bandung: Puslitbang Perumahan dan Pemukiman) pp 23–6

[26] Goto C and Ogawa Y 1997 Propagation in The Ocean in the Spherical Co-ordinates Tsunami-F1 and Its Programme List (Sendai Japan)

[27] Imamura F, Yalçiner A C and Ozyurt G 2006 Tsunami Modelling Manual (Sendai Japan)

[28] Wells D L and Coppersmith K J 1994 New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement vol 84

[29] Badan Informasi Geospasial 2018 Peta BATNAS dan DEMNAS (Jakarta)

[30] Power W and Leonard G S 2013 Tsunami Encyclopedia of Earth Sciences Series (Springer Netherlands) pp 1036–46

[31] Prawiranegara M 2020 Harmonisasi Kebijakan Penataan Ruang Pesisir Berbasis Mitigasi Bencana antara Pemerintah Pusat dan Daerah

[32] Zuhdi M, Makhrus M, Sutrio S and Wahyudi W 2019 Sosialisasi Tentang Mitigasi Bencana Tsunami dan Gempa Lombok Di Jempong Baru, Sekarbela, Mataram Jurnal Pengabdian Magister Pendidikan IPA 2 6–10

[33] BPBD Provinsi NTB 2019 Perkuat Mitigasi, Perencanaan Pembangunan Berbasis Kebercandaan Perlu Dilakukan di NTB Website BPBD Provinsi NTB

Author Contribution
The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the data and the paper are free of plagiarism. In carry out this study and write this paper Mardi Wibowo is the main author and the other ones are supporting contributors.

Acknowledgments
The authors would like to thank the management of BTIPDP-BPPT, the Project Director, Chief Engineer, and the Program Manager, as well as all the researchers and engineers involved in the InaTEWS Project at BPPT.