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Assessment of Tsunami Potential in Bali Using TOAST Modeling: Implications for Disaster Risk Reduction

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Abstract: This study aims to evaluate the tsunami hazard potential in the Bali region using multi-scenario numerical modeling to support disaster mitigation and early warning planning. Tsunami simulations were performed using the Tsunami Observation and Simulation Terminal (TOAST) with the EasyWave module. The model inputs were derived from the BMKG historical earthquake catalog and the 2017 Indonesian Seismic Hazard Map (PUSGEN), focusing on the Flores Back Arc Thrust segment north of Bali. Four earthquake magnitude scenarios (Mw 7.0, 7.2, 7.5, and 8.5) were simulated to estimate maximum wave heights and tsunami arrival times along the Bali coastline. The results indicate that nearly all coastal areas of Bali are vulnerable to tsunami impacts. In the worst-case scenario (Mw 8.5), maximum wave heights exceed 5 m in Sanur (Denpasar), Klungkung, and southern Karangasem, with short arrival times ranging from 5 to 22 minutes, corresponding to the highest warning level. Although moderate-magnitude scenarios (Mw 7.0–7.5) generate lower wave heights, tsunami arrival times remain rapid, indicating limited evacuation opportunities. These findings highlight the urgency of multi-scenario tsunami hazard assessment, enhancement of tsunami early warning systems, and improvement of evacuation preparedness to reduce tsunami risk in Bali.

Keywords: Tsunami hazard; TOAST modeling; Bali, disaster risk reduction; and early warning system.

Pendahuluan

Natural disasters constitute a major challenge to sustainable development, particularly in tectonically active regions. In Indonesia, earthquakes and tsunamis represent significant natural hazards due to their sudden onset and extensive impacts on society, the economy, and critical infrastructure (Satake, 2015; Kusumayudha, 2019). Tsunamis are complex hydrodynamic phenomena generated primarily by vertical seafloor displacements associated with large earthquakes, submarine volcanic activity, or underwater landslides (Lay et al., 2005).

Indonesia is among the countries with the highest tsunami risk worldwide, owing to its location at the convergence of the Indo-Australian, Eurasian, and Pacific plates. Subduction processes along these plate boundaries form an active island-arc system characterized by frequent seismic and volcanic activity (Hall, 2012; McCaffrey, 2009). Catastrophic events such as the 2004 Aceh tsunami (Mw 9.1), which caused more than 230,000 fatalities, clearly demonstrate the destructive potential of tsunamis in the region (Lay et al., 2005; Okal, 2006). Subsequent events, including the 2006 Pangandaran and 2018 Palu tsunamis, further revealed the complexity of tsunami generation mechanisms and the influence of bathymetry and coastal morphology on wave amplification and inundation patterns (Fritz et al., 2007; Gusman et al., 2019; Widiyantoro et al., 2020).

Geotectonically, Bali is exposed to tsunami hazards from two major sources: the Sunda megathrust

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subduction zone to the south and the Flores Back Arc Thrust system to the north. Historical records indicate that tsunami events in 1815, 1857, and 1917 caused considerable damage to coastal areas of Bali, underscoring the long-standing tsunami threat in the region (Daryono, 2011; Riyanti, 2017). Despite this vulnerability, tsunami hazard assessments for Bali remain relatively limited compared to other high-risk regions in Indonesia, such as Sumatra and Sulawesi (Løvholt et al., 2015; Annaka, 2021).

Previous tsunami studies in Indonesia have predominantly focused on the Sunda megathrust system, while investigations related to Bali are often restricted to specific locations, single-event scenarios, or simplified source models. Comprehensive assessments that incorporate multiple earthquake magnitudes and systematic scenario-based simulations for the Flores Back Arc Thrust are still scarce. As a result, spatial variations in tsunami impact along the Bali coastline are not yet fully characterized, limiting their usefulness for mitigation and planning purposes.

Advances in numerical tsunami modeling since the 2004 Indian Ocean tsunami have significantly improved hazard assessment capabilities, particularly through the development of efficient simulation tools and their integration with early warning systems (Satake, 2015; Yadav et al., 2022). The Tsunami Observation and Simulation Tool (TOAST) enables rapid multi-scenario simulations and has proven effective for regional-scale tsunami hazard analysis. However, its application for multi-magnitude tsunami modeling in the Bali region, particularly for sources associated with the Flores Back Arc Thrust, remains limited.

Therefore, this study aims to simulate tsunami scenarios generated by multiple earthquake magnitudes using historical data and source parameters from PUSGEN 2017 for the Flores Back Arc Thrust segment. The objectives are to evaluate tsunami wave characteristics along the Bali coastline, identify areas with higher tsunami hazard potential, and provide scientific support for tsunami mitigation strategies, evacuation planning, and the enhancement of tsunami early warning systems in Bali.

Metode

This study applies a quantitative, scenario-based numerical modeling approach to evaluate tsunami hazard potential along the Bali coastline using the Tsunami Observation and Simulation Terminal (TOAST). TOAST, equipped with the EasyWave module, simulates tsunami generation and propagation based on bathymetric input data and outputs maximum wave heights and tsunami arrival times at coastal locations (BMKG, 2017).

Earthquake source parameters were derived from the BMKG earthquake catalog and the 2017 Indonesian Seismic Hazard Map (PUSGEN), focusing on the Flores Back Arc Thrust as a major tsunami-generating structure affecting Bali. Simulations were conducted for earthquake magnitudes of Mw 7.0, 7.2, 7.5, and 8.5 at a fixed depth of 15 km, representing moderate to worst-case scenarios. The multi-magnitude approach was adopted to capture variability in tsunami impact and warning levels.

The simulation domain covers the entire coastline of Bali, with observation points distributed along key coastal areas, including Sanur, Klungkung, Karangasem, Gianyar, and Buleleng. The modeling workflow—comprising source definition, parameter input, tsunami propagation, and extraction of wave height and arrival time—is illustrated in Figure 1.

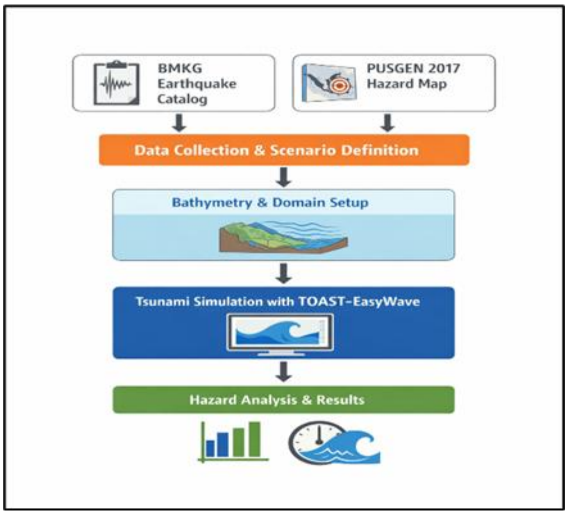

Figure 1. Workflow of tsunami hazard assessment using the TOAST model

Model validation was performed through qualitative comparison with documented tsunami characteristics in Indonesia. Limitations of this study include uncertainties in earthquake source parameters and the use of bathymetric data with limited resolution, which may not fully represent small-scale coastal features.

Hasil dan Pembahasan

The modeling results for the main Mw 8.5 scenario indicate that most coastal areas of Bali are potentially affected by tsunami waves, with maximum wave heights reaching 5.64 m at Sanur Beach (Denpasar), 4.07 m in Klungkung, and 3.86 m in southern Karangasem. The simulated tsunami arrival times are relatively short, ranging from 5 to 22 minutes, placing several coastal segments under the "Warning" category. The detailed simulation results for the Mw 8.5 scenario, including maximum wave height, tsunami arrival time, and warning status at representative coastal locations, are summarized in Table 1. The spatial distribution of tsunami intensity and inundation extent across Bali are illustrated in Figures 1 and 2, respectively.

Tabel 1. Simulation Results of the 8.5 Mw Earthquake Scenario for Bali.

Location	Latitude	Longitude	Maximum Wave Height (m)	Arrival Time (minutes)	Warning Status
Sanur (Denpasar)	-8.68	115.27	5.64	22	Warning
Klungkung	-8.53	115.40	4.07	14	Warning
South Karangasem	-8.44	115.60	3.86	5	Warning
West Buleleng	-8.11	114.88	2.86	0	Advisory
Gianyar	-8.55	115.33	3.69	19	Watch
North Karangasem	-8.25	115.55	2.71	0	Watch

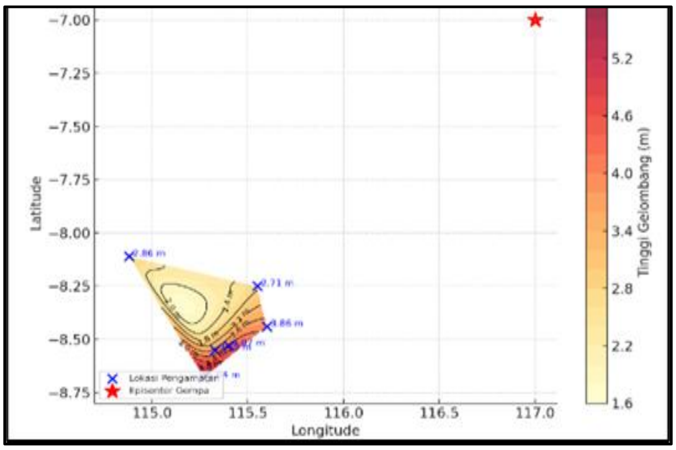

Figure 1. Spatial distribution of tsunami intensity in Bali derived from simulation data interpolation

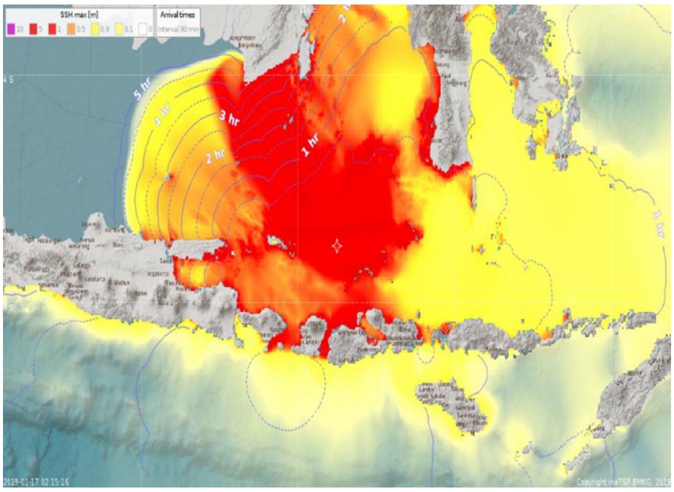

Figure 2. Simulated tsunami inundation map for the 8.5 Mw earthquake scenario in Bali

The spatial variability of wave heights shown in Figure 2 reflects the combined influence of local bathymetry, coastal geometry, and proximity to the Flores Back Arc Thrust source. The southeastern coast of Bali, including Sanur and Klungkung, exhibits higher wave amplification due to shallow nearshore bathymetry and gently sloping coastal plains, which enhance tsunami shoaling effects, consistent with previous tsunami studies in Bali and adjacent regions (Løvholt et al., 2015; Annaka, 2021).

To evaluate tsunami behavior under different seismic conditions, additional simulations were conducted for Mw 7.5, Mw 7.2, and Mw 7.0 scenarios using a simplified magnitude–amplitude scaling approach.

Table 2. Simulation Results of the 7.5 Mw Earthquake Scenario for Bali.

Location	**Latitude**	**Longitude**	**Maximum Wave Height (m)**	**Arrival Time (minutes)**	**Warning Status**
Sanur (Denpasar)	-8.68	115.27	1.78	22	Advisory
Klungkung	-8.53	115.40	1.29	14	Advisory
South Karangasem	-8.44	115.60	1.22	5	Advisory
West Buleleng	-8.11	114.88	0.90	0	Advisory
Gianyar	-8.55	115.33	1.17	19	Advisory
North Karangasem	-8.25	115.55	0.86	0	Advisory

Table 3. Simulation Results of the 7.2 Mw Earthquake Scenario for Bali

Location	**Latitude**	**Longitude**	**Maximum Wave Height (m)**	**Arrival Time (minutes)**	**Warning Status**
Sanur (Denpasar)	-8.68	115.27	1.26	22	Advisory
Klungkung	-8.53	115.40	0.91	14	Advisory
South Karangasem	-8.44	115.60	0.86	5	Advisory
West Buleleng	-8.11	114.88	0.64	0	Advisory
Gianyar	-8.55	115.33	0.83	19	Advisory
North Karangasem	-8.25	115.55	0.61	0	Advisory

Table 4. Simulation Results of the 7.0 Mw Earthquake Scenario for Bali

Location	Latitude	Longitude	Maximum Wave Height (m)	Arrival Time (minutes)	Warning Status
Sanur (Denpasar)	-8.68	115.27	1.00	22	Advisory
Klungkung	-8.53	115.40	0.72	14	Advisory
South Karangasem	-8.44	115.60	0.69	5	Advisory
West Buleleng	-8.11	114.88	0.51	0	Advisory
Gianyar	-8.55	115.33	0.66	19	Advisory
North Karangasem	-8.25	115.55	0.48	0	Advisory

The results, presented in Tables 2–4, enable direct comparison across earthquake magnitudes and demonstrate a consistent reduction in maximum wave height with decreasing magnitude. Statistically, the simulations indicate an approximate 70–80% decrease in wave height between the Mw 8.5 and Mw 7.0 scenarios across all observation points. For example, wave height at Sanur decreases from 5.64 m (Mw 8.5) to 1.00 m (Mw 7.0), while Klungkung shows a reduction from 4.07 m to 0.72 m, confirming a strong magnitude–wave height relationship.

Despite the reduced wave heights in the moderate-magnitude scenarios (Mw 7.0–7.5), tsunami arrival times remain consistently short, with several locations experiencing wave onset in less than 5 minutes. This highlights that limited evacuation time, rather than wave amplitude alone, represents the primary challenge for tsunami risk mitigation in Bali.

When compared with major Indonesian tsunami events, the modeled tsunami characteristics in Bali are more comparable to the 2018 Palu tsunami, which was characterized by extremely short arrival times and rapid coastal inundation (Widiyantoro et al., 2020), than to the 2004 Aceh tsunami, which exhibited longer travel times that allowed more effective evacuation (Lay et al., 2005; Okal, 2006). This similarity underscores the high-risk nature of near-field tsunami sources affecting Bali.

From a practical perspective, these findings highlight the importance of multi-scenario tsunami hazard mapping for Bali. The identification of coastal segments with high wave heights and short arrival times provides essential input for early warning thresholds, evacuation route optimization, and coastal spatial planning, particularly in densely populated and tourism-intensive areas such as Denpasar and Gianyar. Nevertheless, several limitations should be acknowledged. The TOAST simulations rely on simplified earthquake source parameters and bathymetric data with limited spatial resolution, which may not fully capture small-scale coastal features or local topographic effects. In addition, tsunami inundation on land was not explicitly modeled, potentially underestimating localized impacts. Future research should integrate high-resolution bathymetry and topography, more detailed rupture models, and field-based validation to enhance tsunami hazard assessments in Bali.

Kesimpulan

This study successfully demonstrates that multi-scenario tsunami modeling using TOAST provides an effective assessment of tsunami hazard potential along the Bali coastline. The results show that nearly all coastal areas of Bali are exposed to tsunami impacts with short arrival times (<30 minutes). The worst-case scenario (Mw 8.5) generates wave heights exceeding 5 m in Sanur, Klungkung, and southern Karangasem (Warning), while moderate scenarios (Mw 7.0–7.5) produce lower wave heights (0.5–1.8 m) but remain classified as Advisory due to similarly rapid arrival times. Spatial variations are strongly controlled by coastal morphology and local bathymetry, emphasizing the importance of multi-scenario hazard maps, early warning systems, and rapid evacuation planning for tsunami mitigation in Bali. Nevertheless, uncertainties in earthquake source parameters, simplified rupture assumptions, and limited bathymetric resolution represent key limitations. Future studies should integrate high-resolution topography, detailed inundation modeling, and field validation to improve tsunami risk assessment accuracy.

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