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Spatio–Temporal Variability of Multiple Deterministic Tsunami Scenarios in Denpasar City, Bali

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Abstract

Indonesia sits in one of the world's most seismically active regions, making its coastlines especially dense and economically vital areas like Denpasar, Bali, are very vulnerable to tsunamis from major earthquakes. Single deterministic models often fail to represent the range of plausible rupture characteristics of these seismic events. To address this gap, this study creates a near-field, multi-scenario tsunami hazard assessment for the Sanur-Serangan coastal area to represent a range of plausible local rupture characteristics of these maximum-magnitude seismic events. It uses the Method of Splitting Tsunami (MOST) to simulate nine earthquake scenarios with a magnitude of M_w 8.7 from the Sunda Megathrust. The hydrodynamic results show that tsunami waves can reach all locations quickly, often within 30 minutes. While lower-ranking scenarios show moderate localized impacts, extreme upper-ranking scenarios result in significant increases in inundation, with flow depths exceeding 14 meters and flow velocities approaching 500 cm/s. Combining depth and velocity in a vulnerability matrix indicates that up to 16.85 square kilometers could experience a very high damage likelihood during the worst-case events. These findings may provide useful information to support future evacuation planning, temporary evacuation shelter allocation, and building resilience strategies in Denpasar.

Key words: Multiple Deterministic Tsunami Scenarios, Tsunami Modelling.

1. Introduction

Indonesia sits in one of the world's most seismically active regions. Along its southern and western borders, the coastlines are highly susceptible to devastating tsunamis generated by Indian Ocean tectonic megathrusts (Okal & Synolakis, 2008). While the Sunda megathrust represents a persistent threat to the archipelago, its seismic potential varies geographically. Although the 2004 Sumatra-Andaman earthquake demonstrated that the northern segments of this subduction zone can produce M_w 9.2–9.3 events, the 2024 update from the National Center for Earthquake Studies (PusGen) divides the megathrust into distinct regional segments, estimating a maximum potential magnitude of M_w 8.9 specifically for the segments south of Java and Bali, while Sumba segment can produce the earthquake up to M_w 8.5 (PusGen, 2024). In addition, the Flores back-arc thrust represent massive, persistent threats to the archipelago, the specific historical risk to the island of Bali—and its capital, Denpasar—warrants focused

scientific attention (Felix et al., 2022). Historical archives and interdisciplinary geological records indicate that the region has been repeatedly struck by catastrophic tsunamis over the centuries. For example, recent historical research has uncovered records of previously uncharacterized major tsunamis in the Indonesian archipelago dating back to the seventeenth century, emphasizing the long-term recurrence of such unpredictable events (Reid, 2015). More specifically, in Bali, the catastrophic event of November 1815 stands as the deadliest natural disaster in the island's recorded history. During this event, a massive earthquake triggered a cascading sequence of landslides, debris flows, and a localized tsunami that devastated surrounding coastal communities in Bali (Faral et al., 2024). Furthermore, the great outer-rise earthquake of August 1977 (Mw 8.3) south of Sumba generated a massive tsunami that severely impacted the Lesser Sunda Islands, further underscoring the region's acute susceptibility to far-reaching tsunamigenic events (Gusman et al., 2009).

Following the 2004 Indian Ocean Tsunami, significant efforts were made to quantify coastal risks in Bali, most notably through the German-Indonesian Tsunami Early Warning System (GITEWS) project. This initiative, facilitated by the Balinese Working Group for Tsunami Hazard Mapping (Balinese Working Group for Tsunami Hazard Mapping, 2010), produced foundational regional, multi-scenario hazard and inundation maps for southern Bali at a 1:25,000 scale. Subsequent local mapping initiatives have also explored specific coastal enclaves, such as Tanjung Benoa (Anggraini et al., 2026). Despite these crucial baseline efforts, applying these broader regional tsunami hazard assessments to highly localized, densely built urban areas presents significant methodological gaps.

However, applying regional tsunami hazard assessments to localized urban areas presents significant methodological gaps. Contemporary literature emphasizes that traditional hazard and loss models often fall short by relying predominantly on scalar inundation depth, neglecting critical complex hydrodynamic parameters such as flow velocity and specific momentum flux. These parameters are essential for accurate fragility analysis and loss estimation, particularly in highly constructed urban environments where dynamic forces and macro-roughness dictate structural survival (De Risi et al., 2017; Park et al., 2013; Song et al., 2017). Furthermore, bridging the gap between regional hazard assessments and the necessity for high-resolution, site-specific onshore inundation simulations remains a major logistical hurdle (Ruffini et al., 2026).

Furthermore, in the context of the application of multi-scenario tsunami modeling for Bali that accounts for complex near-shore dynamics, there also remains a critical gap. While scenario-based simulations have been successfully employed to assess future megathrust hazards and time-dependent risks in areas like Padang and Sumatra (Muhammad et al., 2016; Muhammad et al., 2017; Muhammad et al., 2022), as well as in other tourist villages like Batukaras (Windupranata et al., 2025), such advanced, hydrodynamic-focused methodologies are rarely applied to the Denpasar coastal region. Without multi-scenario modeling (Behrens et al., 2021; Goda et al., 2016) and localized velocity-dependent vulnerabilities, hazard assessments fail to capture the full spectrum of potential wave impacts, leaving disaster mitigation strategies fundamentally incomplete.

Addressing these critical gaps requires transitioning from conventional single-scenario approaches to a more comprehensive multi-scenario framework that better represents the inherent variability in tsunami generation and propagation. In this context, the first objective of this study is to develop multiple deterministic near-field tsunami scenarios tailored to the complex tectonic setting immediately surrounding Bali, incorporating variability in local earthquake sources, magnitudes, and rupture characteristics for maximum-probable events. Building on this, the study aims to assess hazard variability by capturing a wide spectrum of possible tsunami impacts, particularly in terms of inundation depths and wave arrival times, thereby providing a more robust understanding of potential risk ranges rather than a single deterministic outcome. Finally, the study seeks to map infrastructure exposure across Denpasar, identifying critical assets and vulnerable areas that may be affected under different tsunami scenarios. This integrated approach is intended to support more targeted urban resilience planning and disaster mitigation strategies, ultimately enhancing preparedness and reducing potential losses in coastal communities.

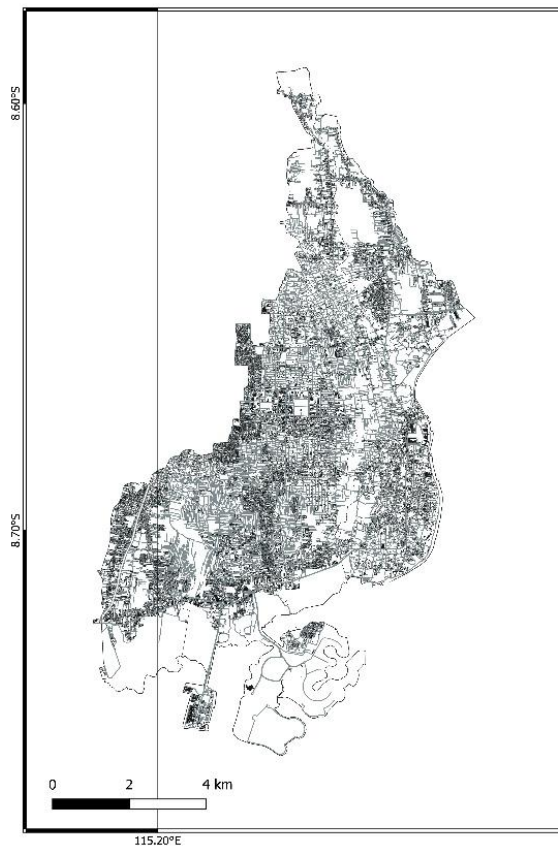
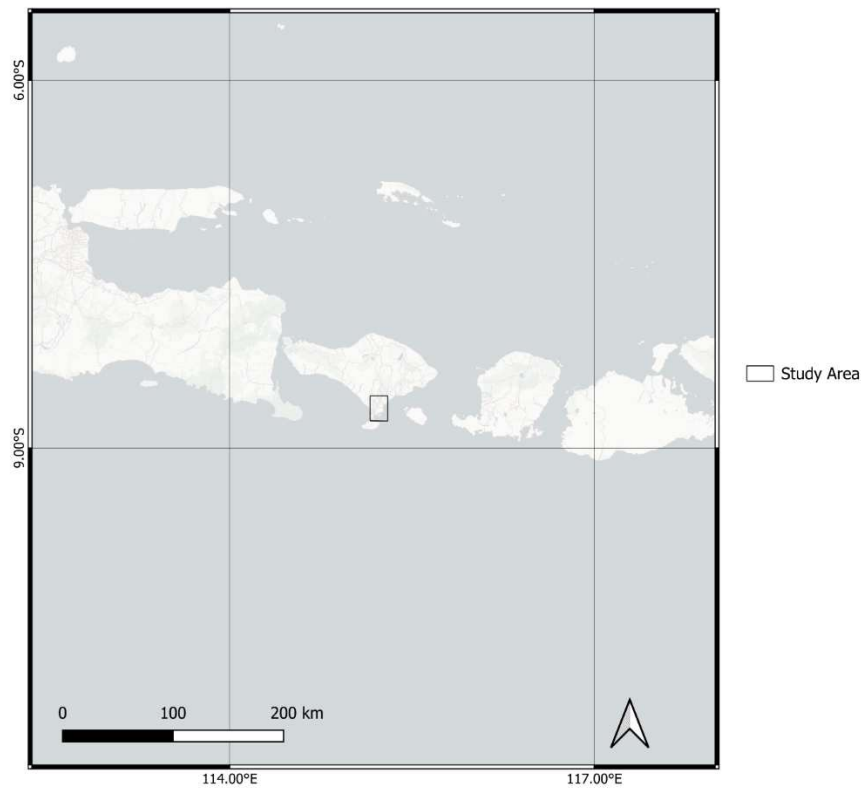


Figure 1 - Study Area – Sanur-Serangan Coast (East and South Denpasar)

Figure 1 shows the location of study area, showing Bali coastal region of Denpasar City. The coastal region of Bali exists within a complex multi-hazard environment. While long-term coastal risks will inevitably be exacerbated by climate-driven sea-level rise, and historical records indicate the region is susceptible to atypical tsunamigenic sources (Hastuti et al., 2022; Anggraini et al. 2026) (such as the 1815 landslide-triggered event generated in the Flores Back-arc), quantifying these compounding and multi-source threats requires highly complex, probabilistic frameworks. However, the most immediate, deterministic, and historically catastrophic threat to the highly populated southern coast of Denpasar City remains a massive co-seismic rupture along the Sunda Megathrust. Therefore, to provide foundational, high-resolution hydrodynamic data, this study strictly bounds its focus to isolating the nearshore propagation and inundation dynamics of deterministic co-seismic megathrust scenarios under current baseline sea-level conditions.

Denpasar is not only a densely populated urban center but also Bali's economic engine, heavily reliant on coastal tourism and related infrastructure. The island's history with crises demonstrates how deeply intertwined its long-term economic recovery is with the resilience of its tourism sector (Gurtner, 2016). Furthermore, the rapid expansion of informal socio-political networks and urban development in Denpasar often outpaces structured disaster risk reduction planning (Henley & Schulte Nordholt, 2015). Because coastal settlement typologies in Indonesia vary significantly in their exposure and adaptive capacity (Mardiatno et al., 2017), the concentration of critical infrastructure, dense residential areas, and high-value tourist assets along Denpasar's low-lying coasts creates a uniquely high-risk environment that requires immediate and high-resolution assessment.

2. Methodology

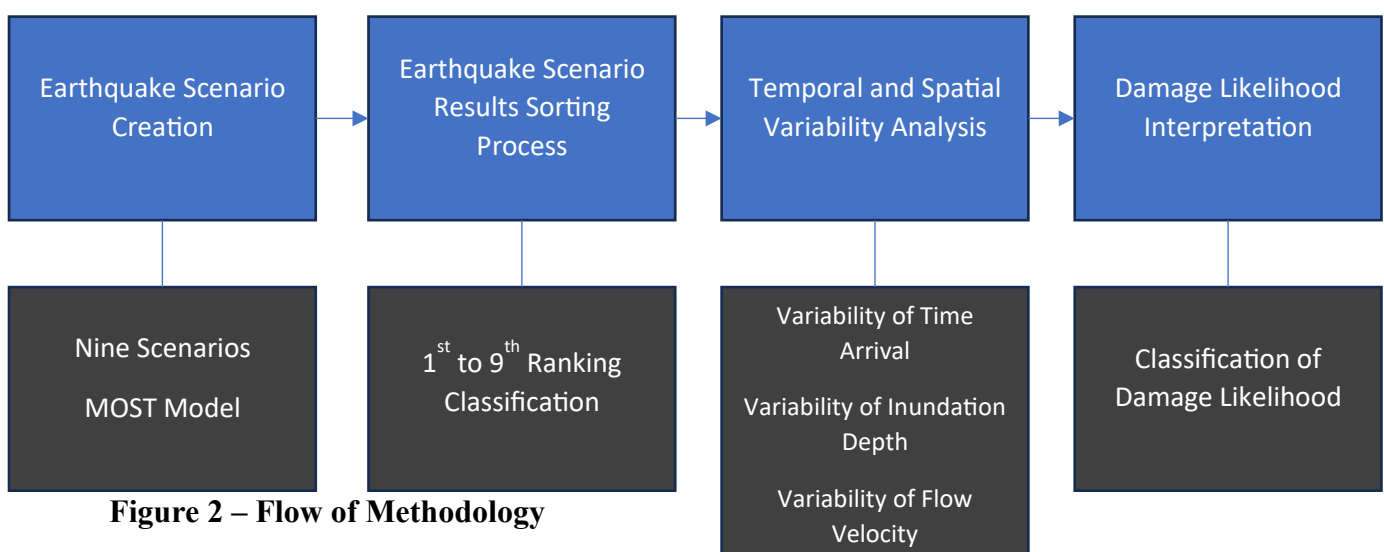


Figure 2 – Flow of Methodology

Figure 2 highlights the flow of the methodology of this study. The methodology begins with Earthquake Scenario Creation, where nine distinct seismic scenarios are generated utilizing the MOST Model. Subsequently, these initial simulations undergo an Earthquake Scenario Results Sorting Process, which organizes the outcomes into a hierarchical 1st to 9th ranking classification. Following this prioritization, a Temporal and Spatial Variability Analysis is conducted to examine critical physical hazard metrics, specifically focusing on the variability of time arrival, inundation depth, and flow velocity. Finally, this spatial and temporal data is synthesized during the Damage Likelihood Interpretation phase, culminating in a final classification of damage likelihood that translates the physical metrics into concrete vulnerability assessments. The details can be seen in the subsequent subsections.

2.1 Earthquake Scenarios Creation

The tsunami simulation is driven by nine distinct deterministic earthquake scenarios originating from the Sunda Megathrust, all anchored to a moment magnitude of M_w 8.7. Setting the maximum-probable earthquake magnitude for a deterministic hazard assessment requires balancing segment-specific models with the potential for long return-period, multi-segment ruptures. According to the 2024 update from the National Center for Earthquake Studies (PusGen, 2024), the maximum credible earthquake for individual, isolated segments in this region is estimated at M_w 8.5. However, relying strictly on historical catalogs and segment boundaries can lead to dangerous underestimations of seismic potential. The 2004 Sumatra-Andaman earthquake clearly demonstrated the risk of discarding larger magnitudes, proving that subduction zones of sufficient length can host catastrophic, multi-segment failures that defy previous empirical limits (McCaffrey, 2008).

Recognizing this, recent geodetic and kinematic studies support the inclusion of larger, multi-segment scenarios. Block motion modeling of the West and East Java megathrust system indicates that convergence with the Indo-Australian Plate can accumulate sufficient slip deficit to generate earthquakes up to M_w 8.7 (Raharja et al., 2024). Furthermore, Widiyantoro et al. (2020) highlighted that if a rupture breaches segment boundaries south of Java, it could plausibly unleash a megathrust earthquake in the range of M_w 8.8 to 9.1. While a comprehensive probabilistic tsunami hazard analysis (PTHA) would index these magnitudes to specific return periods, this deterministic study adopts M_w 8.7 to represent a long return-period event. This choice bridges the gap between the conservative M_w 8.5 individual segment

estimates and the extreme multi-segment potential, providing a robust baseline to assess localized hydrodynamic vulnerabilities in Denpasar.

To define the baseline rupture dimensions for the M_w 8.7 maximum credible earthquake (Scenario 1), the empirical scaling relations for subduction zone earthquakes proposed by Shi et al. (2026) were applied:

$$\log L = -2.82 + 0.62M_w$$

$$\log W = -1.90 + 0.47M_w$$

For an M_w 8.7 event, these empirical equations yield a theoretical rupture length (L) of approximately 375 km and a width (W) of 155 km. For the numerical modeling baseline (Scenario 1), these values were practically adjusted to a maximum bounding area of 400 km x 150 km. The 400 km length was chosen as a conservative upper bound to ensure the rupture fully encompasses the targeted megathrust segments. Furthermore, the 150 km width was selected because it is physically constrained by the downdip extent of the seismogenic interface in this region, as parameterized by the NOAA database. Assuming a shallow subduction dip angle typical of the Sunda Megathrust, a 150 km fault width correctly mimics the seismogenic zone across the specific depth layers utilized in our scenarios, which span from shallower depths of approximately 15.40 km down to a lower seismogenic limit of 36.19 km.

While Scenario 1 represents a standard, empirically derived rupture, Scenarios 2 through 9 (S2–S9) were designed as localized, experimental scenarios. These scenarios do not strictly adhere to the empirical scaling relations for a standard M_w 8.7 event; instead, they were engineered to test the hydrodynamic sensitivity of the Denpasar coast to varying epicentral locations and highly concentrated, extreme slip conditions (asperities).

To ensure physical validity, all experimental scenarios strictly conserved the total seismic moment for an M_w 8.7 event using the seismic moment equation:

$$M_0 = \mu AD$$

Where M_0 is the seismic moment, μ is the crustal shear modulus (rigidity), A is the rupture area ($L \times W$), and D is the average slip. Following Kowalik (1997), a constant rigidity (μ) value of 4.2×10^{11} dyne cm⁻² was applied across all models. Because the overall energy release (M_0) was held constant, any deliberate reduction in the experimental rupture area (A) in Scenarios 2 through 9 dictated a proportional, mathematically required increase in the average slip (D).

Width (km)	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Dip (deg)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Rake (deg)	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
Strike (deg)	277.68	277.68	277.68	277.93	277.93	277.93	271.48	271.48	271.48	270.0	270.01	270.01
Depth (km)	15,40	25,79	36,19	15,40	25,79	36,19	15,40	25,79	36,19	15,40	25,79	36,19

*Segment distribution is based on NOAA databases

Table 2 – Segment Details for Each Scenario

Segments	io49a	io49z	io49y	io50a	io50z	io50y	io51a	io51z	io51y	io52a	io52z	io52y	Average Slip (m)
S1 (400 x 150 km)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	5.540
S2 (300 x 150 km)	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	7.388
S3 (300 x 150 km)	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	7.388
S4 (200 x 150 km)	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO	11.080
S5 (200 x 150 km)	YES	YES	YES	NO	NO	NO	NO	NO	NO	YES	YES	YES	11.080
S6 (200 x 150 km)	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	11.080
S7 (300 x 100 km)	YES	YES	NO	YES	YES	NO	YES	YES	NO	NO	NO	NO	11.080
S8 (300 x 100 km)	NO	NO	NO	YES	YES	NO	YES	YES	NO	YES	YES	NO	11.080
S9 (300 x 100 km)	NO	YES	YES	NO	YES	YES	NO	YES	YES	NO	NO	NO	11.080

*YES if the segment is used for the scenario

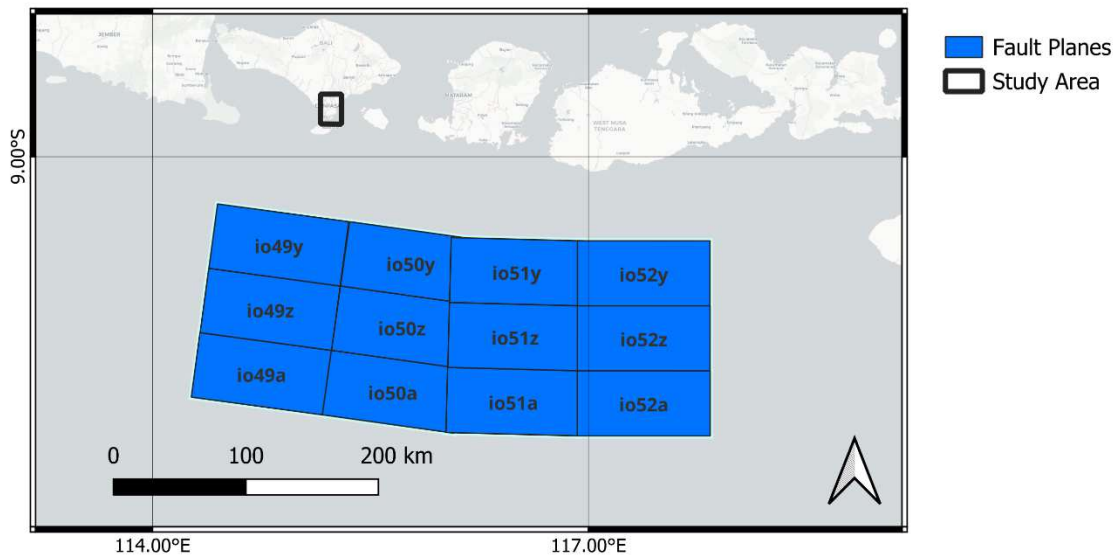


Figure 3 – Fault Segments and Distribution Relative to the Study Area

In addition, the nine deterministic rupture scenarios were designed to represent a range of physically plausible megathrust rupture configurations along the southern Bali subduction interface. Scenario selection considered variations in rupture segmentation, slip concentration, and spatial distribution to capture representative tsunami generation characteristics relevant to

the Denpasar coastal region. The number of scenarios was intentionally limited to balance computational efficiency with the need for high-resolution inundation modelling and detailed hydrodynamic analysis.

2.2 Tsunami Numerical Simulation

The tsunami generation, propagation, and inundation were modeled using the MOST (Method of Splitting Tsunami) numerical model. MOST uses the nonlinear shallow-water equations to simulate wave dynamics from the deep ocean to coastal run-up. The numerical model has been extensively validated in previous tsunami studies against historical observations, laboratory experiments, and operational forecasting applications (Titov & González, 1997; Titov et al., 2005; Titov et al., 2016), supporting its robust suitability for simulating the tsunami generation, propagation, and coastal inundation processes in this study.

Model Inputs and Grid Setup

Model Inputs and Grid Setup To efficiently simulate tsunami generation, deep-ocean propagation, and near-shore inundation, the MOST model utilizes a telescoping system of three nested computational grids.

- **Bathymetry and Topography Data:** The computational grids were constructed by integrating regional bathymetry and local high-resolution topography. All offshore and near-shore bathymetric and topographic data were directly derived from the CoMMIT Server database (<https://sift.pmel.noaa.gov/ComMIT>). Beyond the standard subsampling and smoothing procedures described later, the data underwent post-processing to align all vertical datums to Mean Sea Level (MSL) to ensure seamless interpolation across grid boundaries and accurate inundation mapping.
- **Nested Grid Resolutions:** The domain was divided into three nested grids to optimize computational efficiency while preserving near-shore hydrodynamic accuracy. Grid A (regional propagation) has a spatial resolution of 1500 m x 1500 m. Grid B (intermediate transition) covers the coastal shelf surrounding Bali at a resolution of 250 m x 250 m. Grid C (high-resolution inundation) focuses specifically on the Sanur-Serangan study area with a fine spatial resolution of 20 m x 20 m to capture complex overland flow dynamics and urban macro-roughness. The spatial extents and boundaries of these nested grids are illustrated in **Figure 4**. To capture the dynamic

processes accurately, the model outputs were recorded with a time step of 30 seconds per animated frame.

- **Initial Sea Surface Deformation:** The initial static seafloor displacement was computed following the standard assumptions integrated within the CoMMIT software. The software calculates deformation within a homogeneous, isotropic, elastic half-space based on the specified rupture parameters (strike, dip, rake, slip, and dimensions). Consistent with standard shallow-water tsunami generation theory applied within CoMMIT, an incompressible water column is assumed. Therefore, the calculated vertical seafloor deformation is assumed to transfer instantaneously and identically to the sea surface to form the initial tsunami waveform

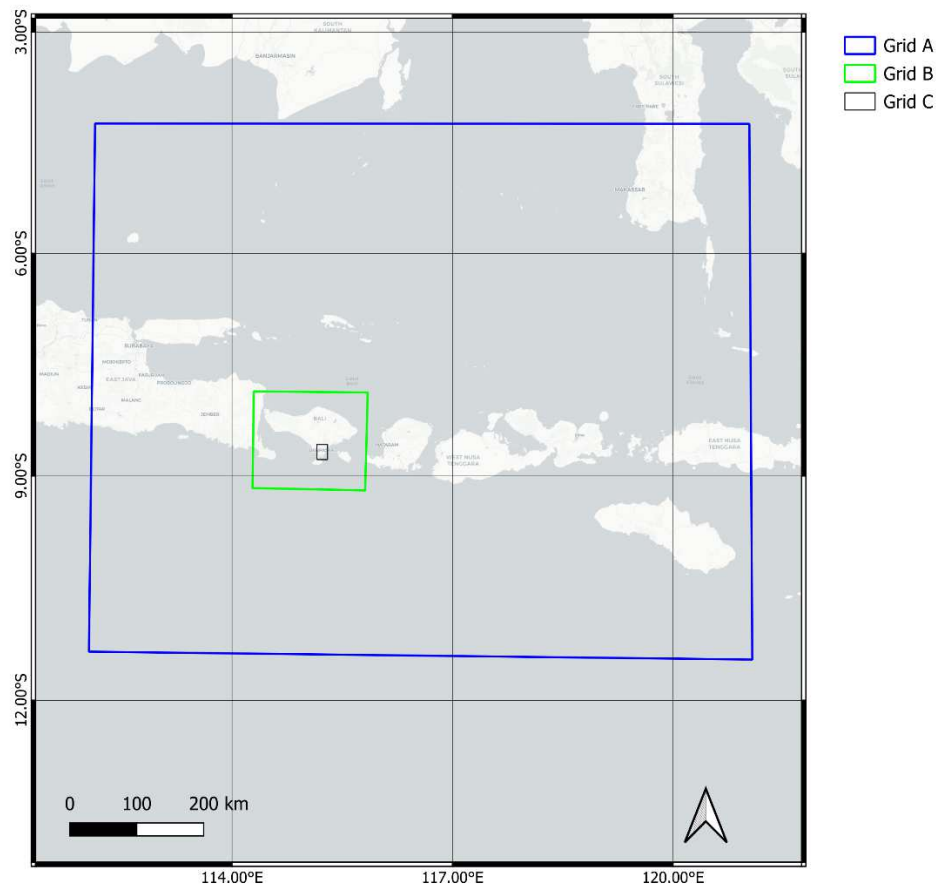


Figure 4 – Nested Grid Coverage

Model Parameters

To ensure numerical stability and computational efficiency, the simulation utilized the following specific boundary conditions and physical parameters:

- **Minimum amplitude of input offshore wave (0.0050 m):** This serves as a computational filter during deep-ocean propagation. Wave amplitudes below 5 mm are considered negligible and are excluded from the calculations to reduce numerical noise and optimize processing time.
- **Minimum depth of offshore (5.0 m):** This parameter establishes the bathymetric threshold where the MOST model transitions its algorithms to handle complex near-shore shoaling. It prevents numerical instability that can occur in extremely shallow offshore grid cells before the wave officially reaches the shoreline.
- **Dry land depth of inundation (0.1 m):** This defines the computational "wet/dry" boundary for overland flow. Flow depths below 10 cm are classified as dry land, which prevents the numerical model from indefinitely calculating microscopically thin, friction-heavy water films that drastically slow down simulation times and cause instability during the run-up phase.
- **Friction coefficient ($n^2 = 0.0009$):** This translates to a Manning's roughness coefficient (n) of 0.03. According to standard coastal engineering practices (e.g., Chow, 1959; Kotani et al., 1998), an n value of 0.03 is widely accepted and recommended for modeling overland flow in coastal plains characterized by light vegetation and typical residential development. It effectively captures the basal friction required to simulate realistic wave attenuation over populated shorelines.
- **Mean Sea Level (MSL):** The initial hydrodynamic condition for all simulations was set to a static Mean Sea Level (MSL) datum, providing a standardized baseline to isolate the influence of the varied earthquake source parameters.

Model Outputs

1. **Time series of wave elevations at ten specific coastal sample points.**

For each of the 9 scenarios, the MOST model generated: Time series of wave elevations at ten specific coastal sample points (detailed in Table 3). These locations were strategically selected to correspond with key socio-economic coastal assets—such as major public beaches, ports, and harbors (e.g., Sanur Beach, Serangan Harbour, Suwung Port)—to assess the immediate threat to highly populated recreational and economic zones. To ensure stable and accurate extraction of the incoming wave profile before complex onshore run-up dynamics occur, these virtual gauges are positioned in the sea,

approximately 100 meters offshore from the coastline. The exact geographic locations of these sample points are plotted in **Figure 5** to provide spatial context for the temporal analysis.

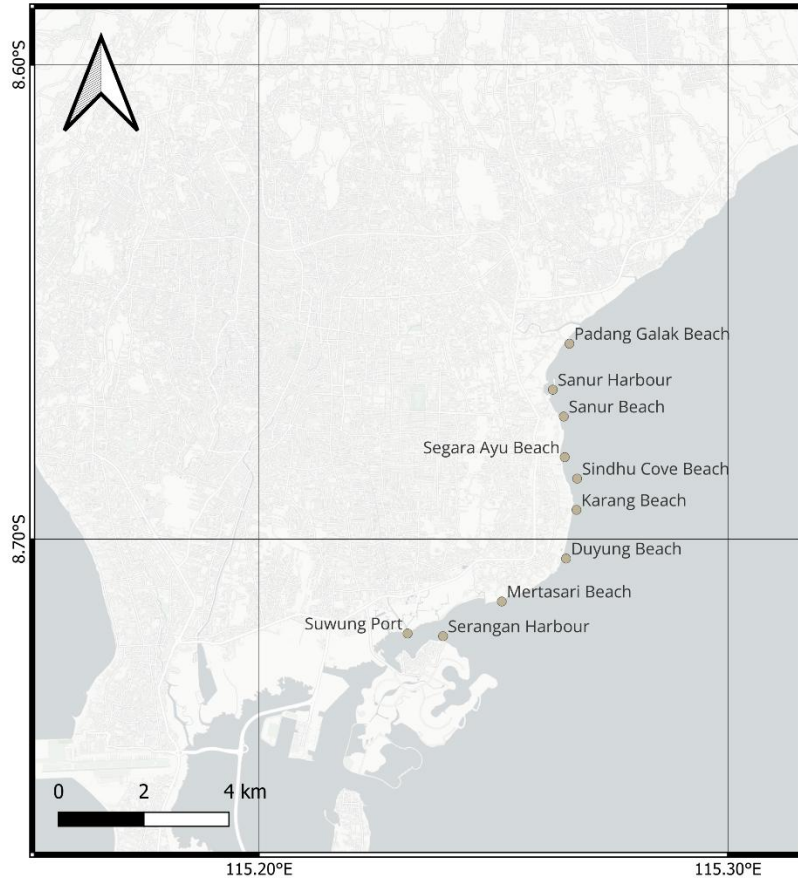


Figure 5 – Virtual Gauge Location

Table 3 – Details of Virtual Gauge Location

No.	Location	Longitude	Latitude	Abbreviation
1	Duyung Beach	115.26547	-8.70408	DUYB
2	Karang Beach	115.26769	-8.69382	KARB
3	Mertasari Beach	115.25176	-8.71313	MERB
4	Padang Galak Beach	115.26619	-8.65877	PGAB
5	Sanur Beach	115.26498	-8.67415	SANB
6	Sanur Harbour	115.26265	-8.66848	SANH
7	Segara Ayu Beach	115.26519	-8.68271	SEGB
8	Serangan Harbour	115.23924	-8.72045	SERH
9	Sindhu Cove Beach	115.26784	-8.68723	SINB
10	Suwung Port	115.23168	-8.71988	SUWP

2. **Spatial Grids** (at a high resolution of 20x20 m) mapping the maximum flow depth, maximum flow velocity, and maximum amplitude across the study area.

Bathymetry Preprocessing

To improve numerical stability and reduce interpolation-related artefacts, the bathymetric dataset used in the MOST simulation underwent preprocessing through bathymetric subsampling and smoothing procedures prior to model execution. Bathymetry subsampling was applied to optimize the computational grid resolution while preserving the dominant coastal and offshore morphological features relevant to tsunami propagation and inundation processes. This approach helps reduce excessive computational noise and improves model efficiency for high-resolution inundation simulations.

In addition, bathymetric smoothing was implemented to minimize unrealistic depth discontinuities and steep gradients that can generate numerical instability in nonlinear shallow-water simulations. The smoothing process preserves the overall geomorphological structure of the coastal system while ensuring stable wave propagation and inundation calculations within the MOST framework. Similar preprocessing approaches are commonly applied in tsunami numerical modelling studies to improve computational robustness and hydrodynamic consistency.

2.3 Scenario Ranking Analysis

To systematically assess the full spectrum of hazard variability, the hydrodynamic results from the nine earthquake scenarios (S1–S9) were evaluated and ranked based on their relative severity across all primary indicators: temporal arrival time (fastest to slowest), offshore maximum amplitude, total inundation extent, flow depth, and flow velocity.

Interestingly, the sensitivity analysis revealed a uniform hazard alignment: the severity ranking of the scenarios remained perfectly consistent across all measured hydrodynamic parameters. For instance, the scenario that produced the largest inundation footprint simultaneously generated the fastest arrival times and highest peak velocities. To provide clear traceability to the seismic sources defined in Table 1, **Table 4** maps the original earthquake scenarios (S1–S9) to their resulting severity rank, with the 1st Rank representing the most severe (worst-case) hydrodynamic impact, scaling down to the 9th Rank (least severe).

Table 4 – Cross-Reference Mapping of Earthquake Scenarios to Severity Ranks

Rank (Severity Level)	Corresponding Earthquake Scenario
1st (Most Severe)	S9
2nd	S7
3rd	S4
4th	S3
5th	S8
6th	S5
7th	S1
8th	S2
9th (Least Severe)	S6

2.4 Hazard Thresholds and Interpretation

To compute the damage likelihood classification across the study area, this study utilized the specific discharge (often referred to as flux, denoted as d), calculated using the formula $d = h \times v$, where h is the flow depth (m) and v is the flow velocity (m/s). It is important to note that the MOST model outputs the maximum flow depth and maximum flow velocity as independent spatial grids, capturing the peak values at each node over the entire simulation period. Because these peak values may not occur concurrently at a given grid node, multiplying the independent maximums ($h_{max} \times v_{max}$) yields a conservative, upper-bound estimate of the specific discharge. While this methodology may lead to localized overestimations of the instantaneous momentum flux, this conservative approach is intentionally adopted in this study to ensure a strict, worst-case baseline for disaster risk reduction and evacuation planning. The resulting specific discharge values (m^2/s) were then mapped to the five severity tiers outlined in Table 5. These thresholds are adapted from established tsunami fragility and vulnerability literature (Aguirre-Ayerbe et al., 2018). Furthermore, the classification represents relative hydrodynamic hazard intensity rather than direct structural damage prediction.

Table 5 – Momentum Flux, Flow Depth, Flow Velocity Range (Aguirre-Ayerbe et al., 2018)

Damage Likelihood Interpretation	d Range (m ² /s)	h Range (m)	v Range (m/s)
Very low (1)	0 – 0.60	0 – 2.5	0 – 0.24
Low (2)	0.60 – 2.16	2.5 – 4	0.24 – 0.34
Medium (3)	2.16 – 3.00	4 – 6	0.34 – 0.50
High (4)	3.00 – 6.64	6 – 8	0.50 – 0.83
Very high (5)	> 6.64	> 8	> 0.83

In addition, although these empirical thresholds were initially calibrated using building damage data from Oman, they are adopted in this study because they are grounded in the fundamental physics of fluid dynamics that drive structural failure universally. Momentum flux, in particular, acts as a robust proxy for the total hydrodynamic forces exerted on a structure, providing a reliable metric for hazard intensity regardless of geographic location.

Nevertheless, it is critical to acknowledge that the structural fragility of the built environment in Denpasar City differs markedly from the Omani context. Balinese coastal infrastructure presents a highly heterogeneous mix of typologies. This includes modern, engineered reinforced concrete structures built for the tourism sector, alongside traditional Balinese pavilions (*Bale*) characterized by open-air designs with wooden pillars, and widespread informal unreinforced brick masonry commonly utilized in residential areas. Regional fragility studies focusing on Indonesian and broader Southeast Asian coastal settings (Suppasri et al., 2011) have demonstrated that these local construction practices heavily influence survivability during a tsunami event. For instance, Suppasri et al. (2011) highlighted that unreinforced masonry and traditional timber-framed structures, which are prevalent in Indonesia, are highly susceptible to collapse at lower inundation depths and flow velocities. This vulnerability is often driven by foundation scour, inadequate lateral load resistance, and hydrostatic pressure accumulation. Conversely, heavily engineered reinforced concrete tourism facilities may withstand significant momentum fluxes without catastrophic structural failure, although they remain vulnerable to severe non-structural damage.

Therefore, while the thresholds from Aguirre-Ayerbe et al. (2018) provide a standardized, physics-based metric for mapping hazard intensity across the nine scenarios, they are applied herein as a generalized baseline for estimating physical impact. When interpreting the resulting damage-likelihood maps for Denpasar City, these outputs should be viewed as a

conservative proxy for structural risk. Given the distinct fragility characteristics documented in regional literature, it is highly probable that severe damage to traditional and unreinforced local buildings could occur at lower hydrodynamic thresholds than those modeled. This underscores the necessity for future localized vulnerability studies to develop empirical fragility curves specific to Balinese architectural typologies.

2.5 Limitations

2.5.1 Aleatoric Uncertainty of Slip Distribution

While this multi-scenario approach provides a robust baseline for localized disaster risk reduction, it is important to acknowledge the inherent aleatoric uncertainties associated with earthquake rupture characteristics. Specifically, this study employs uniform slip distributions across the defined rupture planes for all nine scenarios. Real megathrust earthquakes, however, exhibit highly heterogeneous slip patterns characterized by localized asperities—zones of concentrated, extreme displacement.

Because the Denpasar coastal region is situated in the near-field of the Sunda Megathrust, the resulting tsunami hydrodynamics are acutely sensitive to these spatial variations in slip. The primary implication of relying on uniform slip models is that the simulated metrics effectively smooth out the peak wave energies. Consequently, this assumption may underestimate peak inundation depths and localized maximum flow velocities in coastal segments located directly adjacent to a potential high-slip asperity, while potentially overestimating the hazard in areas opposite low-slip zones.

Although the experimental scenarios in this study (such as S4 through S9) partially act as a proxy for asperities by forcing artificially high, concentrated slip into smaller overall rupture areas, the energy distribution remains uniform at the patch scale. Therefore, while these deterministic scenarios are critical for establishing baseline evacuation and structural retrofitting thresholds, future high-resolution assessments should integrate stochastic, heterogeneous slip models to fully capture the aleatoric uncertainty of near-field wave amplification.

2.5.2 No Local Field Survey Validation

Because this study evaluates potential future extreme events that exceed historical observations for this specific coastline, local field survey validation of these exact inundation extents is not currently possible.

Historical events, such as the 1815 Bali tsunami and the 1977 Sumba earthquake, firmly establish the region's broader historical vulnerability to tsunamigenic hazards. However, it is crucial to distinguish between the physical parameters of these historical events and the focus of this study. The 1815 Bali tsunami was generated by a rupture along the Flores Back-arc Thrust located to the north of the island. In contrast, Denpasar City is situated on the southern coast and is primarily exposed to the hazard posed by the Sunda Megathrust to the south. Furthermore, historical records indicate that the tsunami generated by the 1977 Sumba earthquake did not affect Denpasar (International Tsunami Information Center, 1977). Because the source locations, propagation paths, and impacted coastlines of these historical events differ fundamentally from the localized megathrust scenarios explored in this study, direct validation or comparative height analysis against the 1815 or 1977 records is not applicable. The scenarios modeled herein are exclusively designed to evaluate the deterministic hazard of the Sunda Megathrust directly impacting Denpasar City.

2.5.3 Model Assumption and Scope

The assessment relies on a limited set of nine deterministic earthquake scenarios constrained to a fixed magnitude (M_w 8.7). Consequently, it does not incorporate a Probabilistic Tsunami Hazard Assessment (PTHA) that would account for the statistical likelihood of such events. The findings are also subject to inherent uncertainties regarding assumed rupture geometries and slip distributions. As noted, because these extreme worst-case scenarios exceed recent historical records for the study area, the results remain model-based projections lacking direct validation against empirical post-event survey data. Finally, this hazard assessment focuses exclusively on physical hydrodynamic parameters—specifically inundation depth, flow velocity, and arrival times. It does not integrate dynamic risk variables such as structural vulnerability, demographic exposure, human evacuation behavior, or socioeconomic factors. Future multidisciplinary research should aim to couple these high-resolution hydrodynamic outputs with comprehensive vulnerability and evacuation models to build a more holistic disaster risk profile for Denpasar.

As noted in the previous subsection (model parameter), the current simulations utilize a static Mean Sea Level (MSL) and focus exclusively on co-seismic megathrust sources. While the broader coastal risk landscape of Denpasar is undeniably influenced by the compounding effects of future sea-level rise, tidal variations, and potential submarine landslide triggers, quantifying these non-seismic and compounding variables falls outside the strict deterministic scope of this study. The primary objective herein was to isolate the hydrodynamic influence of fault geometry and spatial rupture parameters. Consequently, the results presented should be viewed as a foundational co-seismic hazard baseline. Future interdisciplinary research is highly encouraged to build upon this baseline by integrating climate-compounded sea-level projections and multi-source (e.g., landslide-triggered) probabilistic scenarios to capture the full spectrum of Denpasar's coastal vulnerability.

2.5.4 Static Mean Sea Level Usage

All simulations in this study were executed using a static Mean Sea Level (MSL) initial condition. While this baseline approach effectively isolates the specific impact of varying fault geometries on tsunami propagation, it does not account for the tidal stage at the time of wave arrival. In low-lying coastal and lagoon environments, such as the Serangan–Suwung area, inundation extent and depth are highly sensitive to the ambient still-water level. Consequently, while the present results are robust for comparative sensitivity analysis, future assessments aimed directly at comprehensive Disaster Risk Reduction (DRR) planning should incorporate storm-surge-coincident scenarios to evaluate the absolute worst-case inundation limits.

3. Results

3.1 Temporal Variability

The ranking distribution of tsunami arrival times across the ten coastal locations (Table 6) shows a relatively narrow temporal range and clear spatial consistency in the timing of early impact, with all values expressed in minutes (hh:mm:ss). At the higher ranking (1st–3rd), arrival times generally fall between ~23 and 31 minutes, indicating that tsunami waves can reach all sites rapidly after generation, leaving a limited evacuation window. Among the locations, Suwung Port (SUWP) and Serangan Harbour (SERH) tend to exhibit slightly longer arrival times (reaching up to ~38 minutes at the 9th rank), while areas such as Duyung Beach (DUYB) and Karang Beach (KARB) consistently experience earlier wave arrivals, in some cases as fast as ~23 minutes.

This limited temporal variability across the scenarios is directly attributable to the geographical constraints of the selected seismic sources. As depicted in the fault plane map (Figure 3), all nine scenarios are strictly confined to the near-field zone directly south of Bali, utilizing a concentrated cluster of subduction segments (io49 through io52). Because this study deliberately focuses on localized, near-field maximum-magnitude threats rather than testing a wide geographical range of far-field sources, the wave propagation distances from the rupture interface to the Denpasar coast remain relatively constant. Consequently, while inundation depths and flow velocities fluctuate significantly based on varying slip concentrations and rupture dimensions, the tsunami arrival time is almost exclusively dictated by this near-field proximity. Overall, the results highlight a critical early-warning constraint: evacuation planning must assume a response time of less than 30 minutes in most areas, reinforcing the need for efficient, immediate evacuation strategies in the Sanur–Serangan coastal zone

Table 6 – Tsunami Arrival Time (hh:mm:ss)

Rank	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
DUYB	00:23:07	00:23:07	00:23:38	00:23:38	00:24:09	00:24:40	00:27:15	00:27:46	00:28:48
KARB	00:23:38	00:23:38	00:24:09	00:24:09	00:24:40	00:25:11	00:27:46	00:28:17	00:29:19
MERB	00:25:42	00:25:42	00:26:13	00:26:13	00:26:44	00:26:44	00:29:50	00:30:52	00:31:23
PGAB	00:27:15	00:27:15	00:27:46	00:27:46	00:28:17	00:28:17	00:31:54	00:32:25	00:32:25
SANB	00:26:13	00:26:13	00:26:44	00:26:44	00:27:15	00:27:15	00:30:21	00:30:52	00:31:54
SANH	00:27:15	00:27:15	00:27:46	00:27:46	00:28:17	00:28:17	00:31:23	00:31:54	00:32:25
SEGB	00:25:11	00:25:11	00:25:11	00:25:42	00:26:13	00:26:13	00:29:19	00:29:50	00:30:52
SERH	00:27:46	00:27:46	00:28:48	00:28:48	00:29:50	00:29:50	00:31:54	00:33:26	00:35:30
SINB	00:24:40	00:24:40	00:25:11	00:25:11	00:26:13	00:26:13	00:28:48	00:29:19	00:30:21
SUWP	00:29:50	00:30:21	00:31:23	00:31:54	00:32:56	00:33:26	00:34:28	00:36:01	00:38:36
Average	00:26:04	00:26:07	00:26:41	00:26:47	00:27:27	00:27:37	00:30:18	00:31:04	00:32:09
Arrival Time									

To better understand the propagation dynamics and coastal impact of the tsunami, an analysis of the time series was conducted to determine the arrival sequence of the peak waves. Table 7 summarizes which wave in the sequence (first, second, or third) generated the maximum amplitude at each of the ten observation points across the nine rupture scenarios (S1–S9).

The results demonstrate that the maximum tsunami amplitude does not uniformly occur during the first wave arrival. Instead, the timing of the peak amplitude varies significantly depending on the rupture scenario and the specific coastal location. For a majority of the combinations,

the maximum amplitude is delayed and occurs during the third wave (e.g., at Duyung Beach [DUYB] and Karang Beach [KARB] across nearly all scenarios). However, the first wave is responsible for the peak amplitude in specific instances, such as at Sanur Harbour (SANH) during Scenarios 2, 6, and 9, and at Padang Galak Beach (PGAB) during Scenarios 4, 5, 7, and 9. Furthermore, locations like Serangan Harbour (SERH) and Mertasari Beach (MERB) frequently experience their maximum inundation during the second wave. This spatial and temporal variability highlights the complex local wave dynamics, including coastal reflection, refraction, and bathymetric resonance, which significantly influence how tsunami energy is distributed upon reaching the shoreline.

Table 7 - The wave sequence corresponding to the maximum tsunami amplitude at each observation location across all nine scenarios (S1–S9)

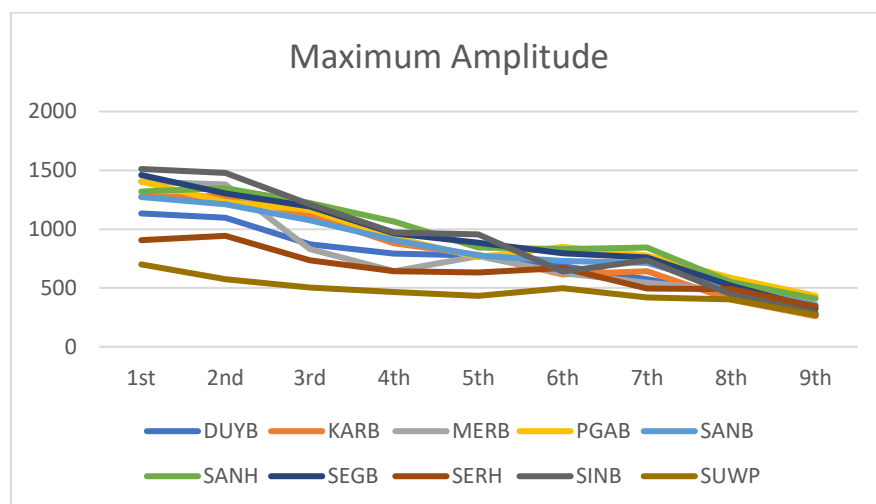
	S1	S2	S3	S4	S5	S6	S7	S8	S9
SANH	3rd wave	1st wave	3rd wave	3rd wave	3rd wave	1st wave	3rd wave	3rd wave	1st wave
SANB	3rd wave	1st wave	3rd wave	3rd wave	1st wave	1st wave	3rd wave	3rd wave	3rd wave
DUYB	3rd wave	3rd wave	3rd wave	3rd wave	3rd wave	1st wave	3rd wave	3rd wave	3rd wave
KARB	3rd wave	3rd wave	3rd wave	3rd wave	3rd wave	1st wave	3rd wave	3rd wave	3rd wave
MERB	3rd wave	3rd wave	3rd wave	2nd wave	2nd wave	3rd wave	2nd wave	2nd wave	2nd wave
PGAB	3rd wave	3rd wave	3rd wave	1st wave	1st wave	3rd wave	1st wave	3rd wave	1st wave
SEGB	3rd wave	1st wave	3rd wave	3rd wave	1st wave	1st wave	3rd wave	3rd wave	3rd wave
SERH	2nd wave	3rd wave	2nd wave	2nd wave	3rd wave	3rd wave	2nd wave	2nd wave	3rd wave
SINB	3rd wave	1st wave	3rd wave	3rd wave	3rd wave	1st wave	3rd wave	3rd wave	3rd wave
SUWP	3rd wave	3rd wave	3rd wave	3rd wave	3rd wave	3rd wave	2nd wave	3rd wave	3rd wave

3.2 Spatial Variability

The ranking distribution of maximum amplitude across the ten coastal locations in Sanur–Serangan shows a clear spatial variability and progressive intensification toward the upper ranking, with all values expressed in centimeters, shown in Table 8. At the lower bound (9th rank), maximum amplitude range from approximately 260–410 cm, indicating a relatively moderate initial impact across sites, with Sanur Harbour (SANH) already exhibiting higher baseline exposure than others. Moving toward the median range (4th–6th rank), most locations show a steady increase in maximum amplitude, generally reaching ~600–1000 cm, reflecting consistent amplification of tsunami intensity across scenarios.

Table 8 - Maximum Amplitude of Each Ranking (in centimeters)

Ranking	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
DUYB	1133,6	1095,61	872,18	792,11	774,84	685,99	575,3	443,13	269,59
KARB	1275,55	1279,91	1117,58	877,92	782,1	615,73	643,4	399,46	260,35
MERB	1403,89	1380,2	829,75	641,2	770,13	626,64	545,02	475,36	278,45
PGAB	1403,85	1229,35	1163,47	927,61	761,93	848,64	774,57	585,51	433,79
SANB	1272,78	1210,01	1075,72	905,82	775,77	730,39	713,33	506,28	356,99
SANH	1319,36	1348,16	1223,24	1064,14	843,96	830,62	842,68	550,24	409,38
SEGB	1459,99	1303,35	1192,88	962,37	885,87	793,84	759,81	519,66	324,6
SERH	906,57	943,32	733,73	642,37	632,37	670,22	496,42	491,04	343,08
SINB	1511,29	1478,92	1212,02	971,08	955,83	638,81	735,68	447,47	288,42
SUWP	700,32	573,95	503,56	466,31	431,82	499,52	420,7	402,02	269,19
Maximum Amplitude	1238,72	1184,28	992,41	825,09	761,46	694,04	650,69	482,02	323,38

**Figure 6 – Maximum Amplitude of Each Place and Ranking**

Based on Figure 6, the upper ranking (1st to 3rd) reveal significant escalation and divergence between sites, highlighting localized vulnerability. Notably, Mertasari Beach (MERB), Segara Ayu Beach (SEGB), and Sindhu Cove Beach (SINB) exhibit the highest extreme values, exceeding 1400–1500 cm at the 1st rank, indicating strong susceptibility to worst-case runup. In contrast, locations such as Suwung Port (SUWP) and Karang Beach (KARB) show comparatively lower upper-bound depths, though still substantial. Overall, the results demonstrate that although all sites are exposed to considerable tsunami runup, the magnitude and escalation rate vary spatially, underscoring the importance of site-specific risk assessment, particularly under high-percentile (extreme) scenarios.

3.3 Inundation Depth and Extent

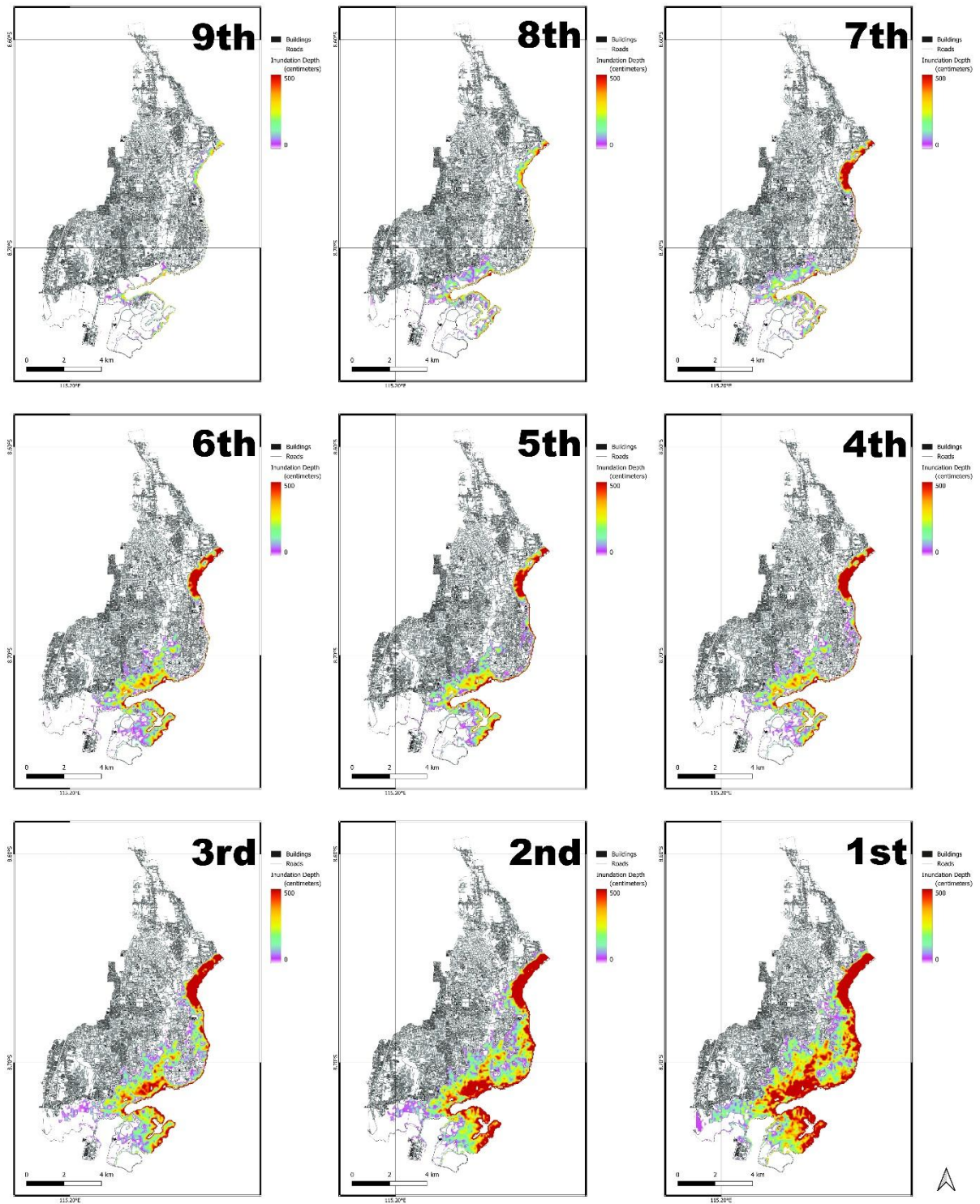


Figure 7 – Maximum Simulated Inundation Depth (1st to 9th rank)

Figure 7 presents a multi-scenario spatial distribution of tsunami inundation depth across the Sanur–Serangan coastal area, where colors represent inundation depth in centimeters (from low values in purple/blue to extreme depths in red). The nine labeled subplots correspond to the scenarios arranged from the least severe (9th Rank) to the most severe (1st Rank), illustrating how tsunami intensity evolves from moderate to extreme conditions.

At the lower ranking (9th to 7th Rank), inundation is limited and highly localized, primarily affecting narrow coastal fringes along the eastern shoreline (Sanur area) and parts of the southern low-lying zones near Serangan and Suwung. The depths in these scenarios remain relatively shallow to moderate, indicating initial wave penetration without extensive inland flooding.

Moving to the middle ranking (6th to 4th Rank), inundation becomes more continuous and spatially extensive, particularly along the eastern coastline and the southern lagoon/estuarine systems. These areas begin to show higher depth intensities (yellow to orange), suggesting increasing flow energy and stronger inland propagation, especially in topographically low and hydraulically connected zones.

In the upper ranking (3rd to 1st Rank), the inundation pattern intensifies significantly, with extensive red zones (>500 cm) dominating the eastern coastal belt and expanding inland toward densely built areas. The southern regions (Serangan–Suwung) also exhibit severe and widespread flooding, forming a continuous high-depth corridor. This indicates that in extreme scenarios, tsunami waves not only deepen but also penetrate farther inland, affecting a much larger proportion of exposed infrastructure and settlements.

3.4 Flow Velocity

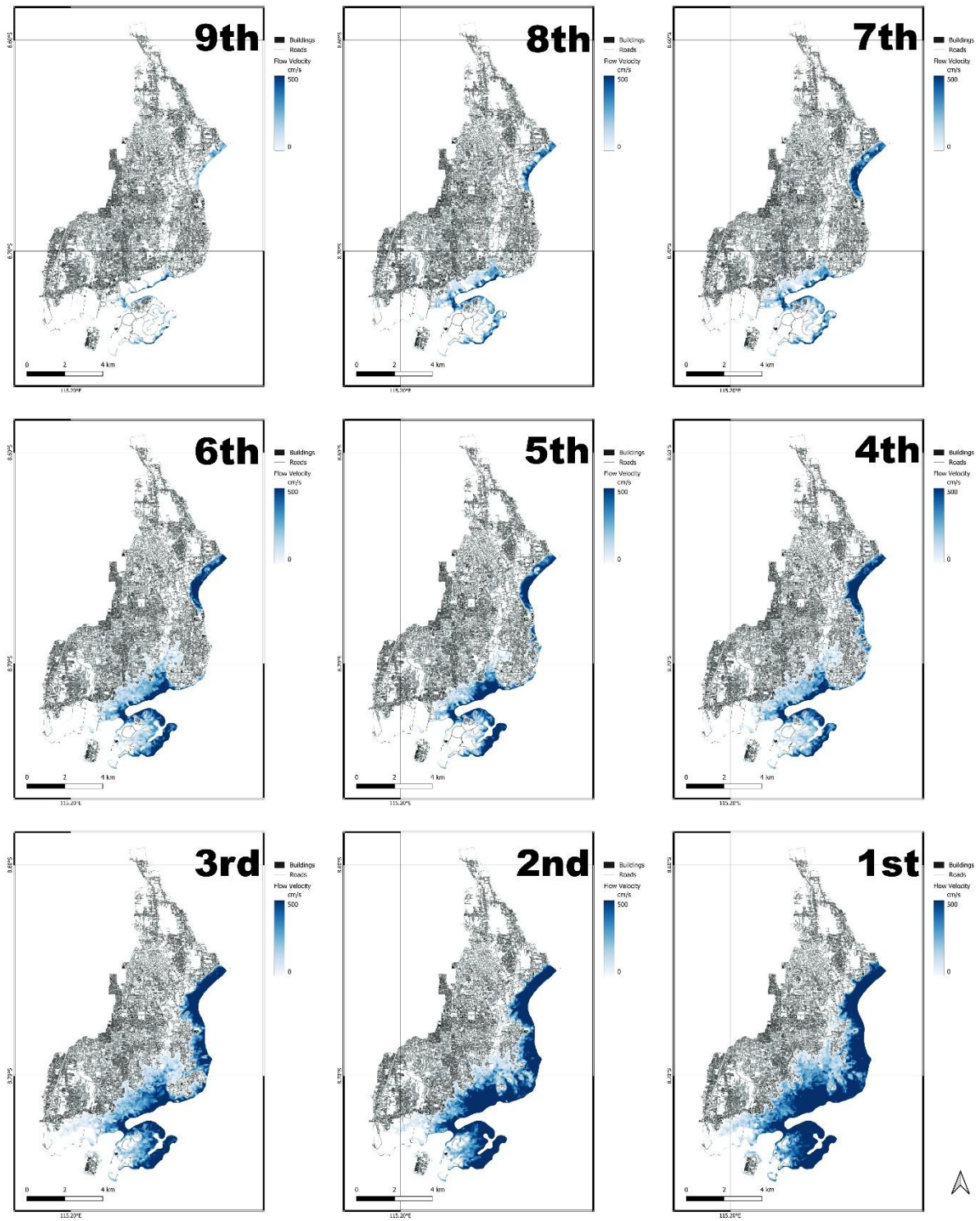


Figure 8 – Maximum Simulated Flow Velocity (1st to 9th rank)

Figure 8 illustrates the spatial distribution of maximum simulated tsunami flow velocity across the Sanur–Serangan coastal area under multiple scenarios, where the blue color gradient represents flow velocity magnitude (cm/s) from low (light blue) to high (dark blue). Similar to the inundation depth maps, the labeled subplots show a progression from the least severe (9th Rank) to the most severe (1st Rank) scenarios, allowing interpretation of how flow dynamics evolve.

At the lower ranking (9th to 7th Rank), flow velocities are generally low and spatially limited, concentrated along the immediate eastern coastline (Sanur area) and parts of the southern lagoon and Serangan region. The inland penetration is minimal, indicating weaker hydrodynamic forcing and limited destructive potential in these scenarios.

In the middle ranking (6th to 4th Rank), flow velocities begin to increase and expand spatially, particularly along the curved eastern shoreline, where coastal geometry appears to focus and accelerate the flow. Additionally, the southern low-lying and semi-enclosed areas (Serangan–Suwung) exhibit higher velocities, suggesting channelized flow and amplification driven by topographic and bathymetric conditions.

At the upper ranking (3rd to 1st Rank), high flow velocities (dark blue, approaching the upper range of ~500 cm/s) become dominant and widespread, especially along:

- The eastern Sanur coastline, forming a continuous high-velocity corridor.
- The southern embayment and lagoon systems, where velocities intensify and spread inland.

These patterns indicate that under extreme scenarios, tsunami waves not only inundate larger areas but also carry significantly higher momentum, increasing the potential for:

- Structural damage
- Scouring and erosion
- Debris transport

3.5 Damage Likelihood Interpretation

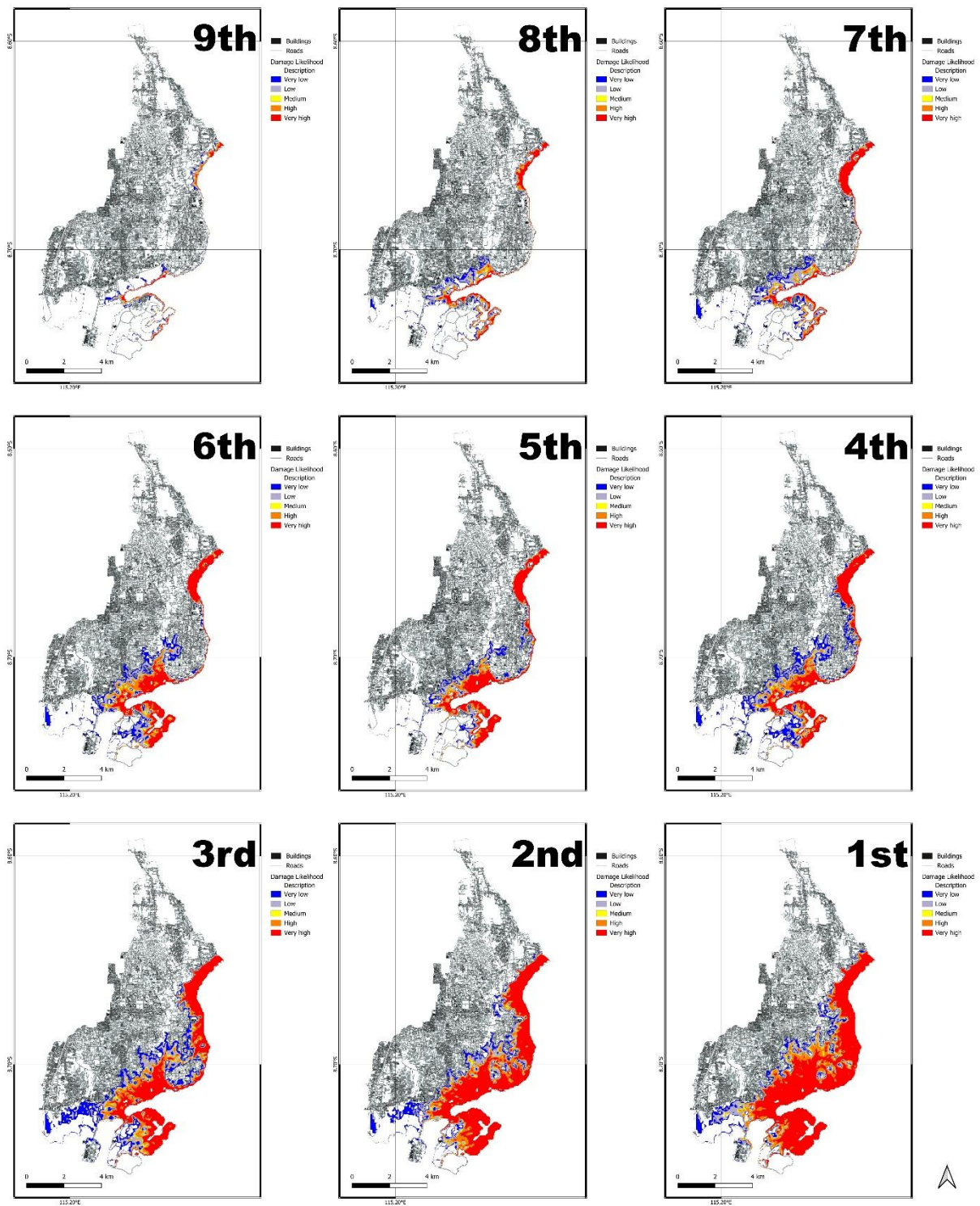


Figure 9 – Damage Likelihood Interpretation

Figure 9 presents the damage likelihood classification derived from the calculated specific discharge ($d = h \times v$), providing an integrated spatial representation of potential tsunami impacts across the Sanur–Serangan coastal area. The labeled subplots are arranged from the least severe (9th Rank) to the most severe (1st Rank) scenarios, with colors indicating damage likelihood levels from very low (blue) to very high (red).

At the lower ranking (9th to 7th Rank), damage is generally limited and localized, with most areas classified as very low to low. Only narrow strips along the eastern coastline and small portions of the southern low-lying zones exhibit moderate to high damage, indicating that although inundation occurs, the combined intensity (depth $\times$ velocity) is still relatively constrained.

In the middle ranking (6th to 4th Rank), the spatial extent of damage increases significantly, with more areas transitioning into medium and high damage categories. The eastern Sanur coastline becomes a consistent hotspot of high to very high damage, while the southern regions (Serangan–Suwung) show expanding zones of elevated damage. This reflects the compounding effect of increasing depth and accelerating flow, which together amplify destructive potential.

At the upper ranking (3rd to 1st Rank), very high damage (red) becomes dominant and widespread, forming a continuous corridor along the eastern coastline and extending deeply into the southern and southeastern inland areas. These zones correspond to areas where both inundation depth and flow velocity are extreme, resulting in the maximum hazard intensity. Meanwhile, some inland pockets remain in low to medium categories, indicating localized attenuation due to topography or distance from primary flow paths.

Table 9 – Total Inundated Area vs Damage Likelihood

Total Area Classified as	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Very High	16,85	12,64	8,86	5,12	5,07	4,92	2,44	1,6	0,53
High	3,73	2,96	3,06	2,24	2,09	1,63	1,25	1,17	0,54
Medium	1,13	0,99	1,1	0,78	0,73	0,55	0,48	0,45	0,2
Low	3,05	3,04	3,2	2,54	2,4	1,81	1,69	1,55	0,68
Very Low	2,58	2,8	2,95	2,82	2,77	1,82	1,5	1,45	0,72
Total Inundated Areas (km²)	27,33	22,43	19,17	13,51	13,06	10,74	7,37	6,22	2,68

Table 9 outlines the total land area, measured in square kilometers, categorized by five levels of tsunami damage likelihood (ranging from "Very Low" to "Very High") across nine distinct ranks for a Serangan-Sanur scenario.

A clear trend in the data is that, as the rank increases from 9 to 1, the total affected area across most risk categories generally increases. The most dramatic and significant growth occurs in the "Very High" damage likelihood classification, which rises from roughly 0.53 square kilometers in the 9th rank to nearly 16.85 square kilometers in the 1st rank. Other categories—such as "High," "Low," and "Very Low"—experience more moderate increases, typically capping out between 2.5 and 3.7 square kilometers. Conversely, the "Medium" risk category consistently covers the smallest geographical footprint across all scenarios, ranging from 0.20 square kilometers at the lowest rank to 1.13 square kilometers at the highest rank. Overall, the data illustrate that in higher rank scenarios, the vast majority of the expanded impact zone falls under the most severe threat level.

4. Discussion

To contextualize the findings of this study within existing national disaster risk frameworks, the modeled inundation extents were compared against established regional hazard products: the 2010 German-Indonesian Tsunami Early Warning System (GITEWS) hazard maps (Figure 10a) and the national InaRISK portal developed by the Indonesian National Board for Disaster Management (BNPB) (Figure 10b).

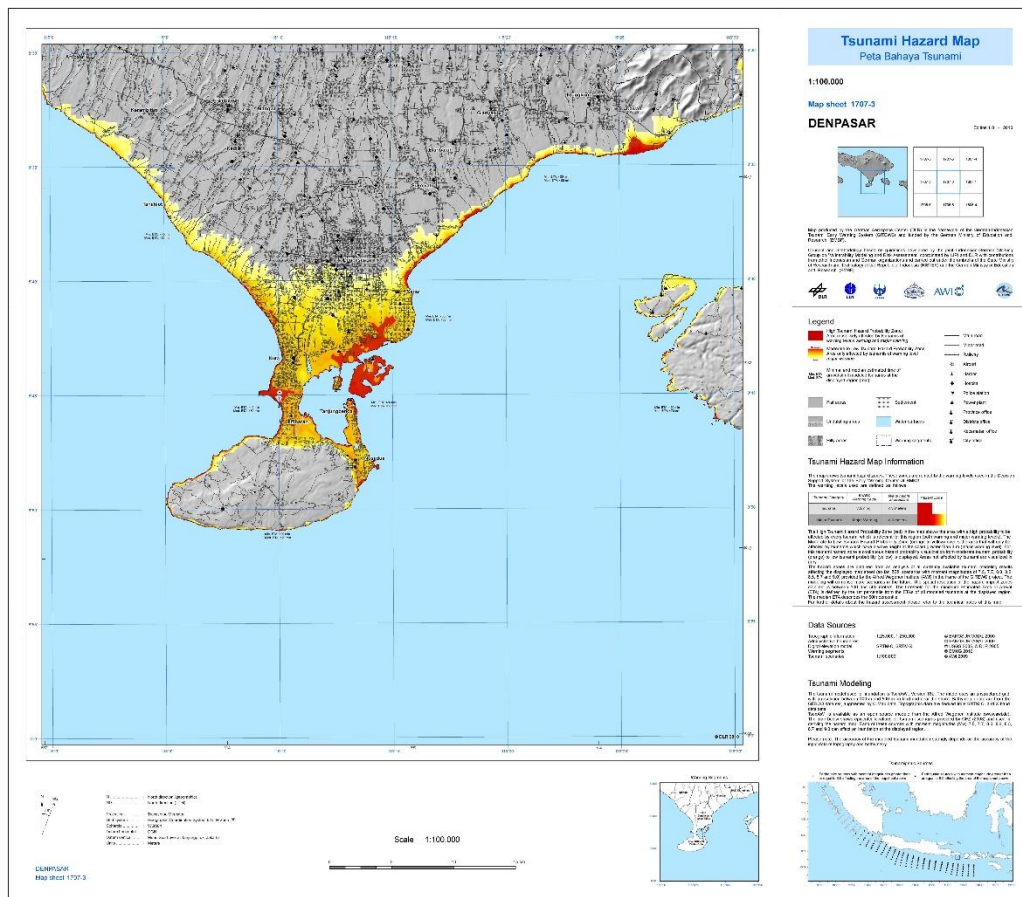


Figure 10a – GITEWS Project Tsunami Hazard Map

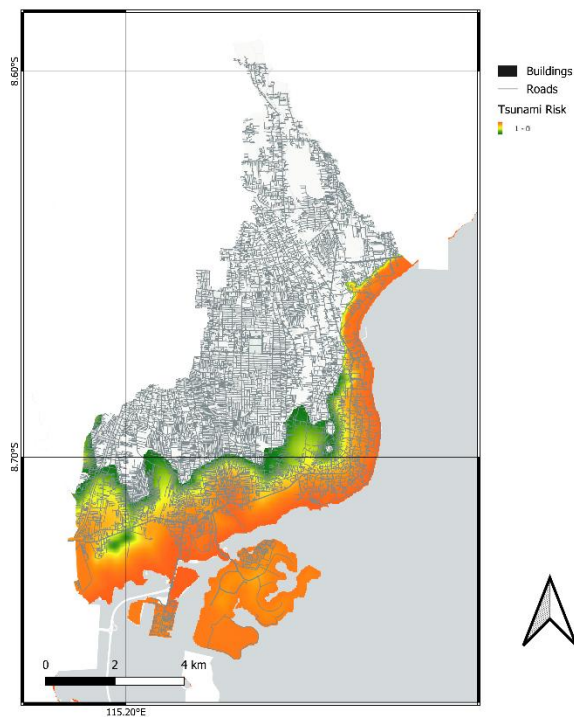


Figure 10b – InaRISK Tsunami Hazard Map

A visual and qualitative comparison reveals a strong spatial agreement between the maximum inundation bounds generated by the deterministic scenarios in this study and the high-hazard zones designated in these national products. Specifically, the extensive inundation over the flat, low-lying topography of the Suwung lowlands, the high vulnerability of Serangan Island, and the severe exposure along the eastern coastline of Sanur are consistently identified across all platforms. This spatial alignment serves as a macro-level validation of the baseline inundation footprint modeled herein.

However, while GITEWS and InaRISK are foundational tools for regional risk communication, they are inherently designed to provide static overviews. These products typically present aggregated, worst-case inundation polygons or generalized risk indices to broadly inform spatial planning. The fundamental added value of the present study lies in its transition from static hazard mapping to high-resolution, spatio-temporal quantification. By explicitly evaluating multiple discrete deterministic scenarios, this study unpacks the dynamic variability that is heavily smoothed over or entirely hidden within aggregated regional maps.

For instance, static inundation maps cannot inform coastal planners about the destructive physical forces buildings will face; this study provides that critical gap by mapping flow velocities and momentum-flux-driven damage likelihoods. Furthermore, as demonstrated in the results section, this study identifies critical temporal variations, such as the fact that maximum tsunami amplitudes frequently occur during the second or third wave arrivals rather than the first. These dynamic, scenario-specific hydrodynamic parameters are absolutely essential for localized structural mitigation design and dynamic evacuation timeline planning. Therefore, this research does not merely duplicate existing vulnerability maps, but rather provides the advanced physical parameters necessary to translate broad risk awareness into targeted, actionable Disaster Risk Reduction (DRR) strategies at the municipal level.

Furthermore, based on the result modelling, it indicates that the hydrodynamic findings for the Denpasar coastal region indicate an extreme, rapid-onset tsunami risk, with maximum inundation depths exceeding 14 meters and flow velocities exceeding 500 cm/s in the worst-case scenarios. Due to the short warning window of under 30 minutes before wave arrival, relying solely on national early warning systems is inadequate. This suggests a paradigm shift toward people-centered disaster risk reduction (DRR) strategies that emphasize immediate self-evacuation (Post et al., 2009; Strunz et al., 2011). Because physical modeling alone often fails to capture true coastal risk without accounting for social preparedness factors, integrated

planning must become a priority for local disaster management authorities (Anggraini et al., 2026).

The spatial extent of the "Very High" damage likelihood zones underscores the necessity for comprehensive urban planning that directly mitigates multi-hazard cascading threats in densely populated areas (Perera et al., 2022). These results may assist local authorities to improve local readiness and foster active social participation to prepare for hazard (Witvorapong et al., 2015). At the administrative level, implementing integrated BIM-GIS disaster management models enables authorities to conduct more effective predictive hazard detection and coordinate resource allocation across these highly vulnerable coastal settlements (Cao et al., 2023).

4.1 Evacuation Route

As demonstrated by the temporal variability analysis, the first tsunami waves can arrive at eastern coastal locations, such as Duyung and Karang Beach, in as little as 23 minutes (Table 6). Given this severely constrained evacuation window, establishing and optimizing shortest-path evacuation routes is critical. Furthermore, the spatial simulations reveal that under extreme scenarios, extensive inundation depths (Figure 7) and high flow velocities (Figure 8) will rapidly compromise primary road networks across the Sanur-Serangan coastal belt.

Because the "Very High" damage likelihood zones (Figure 9) expand deeply inland during maximum-magnitude events, standard vehicular evacuation is highly likely to fail, leading to severe bottlenecks and entrapment before evacuees can reach natural high ground. Therefore, disaster management planning in Denpasar must integrate high-resolution digital elevation models (DEM) to accurately identify viable pedestrian escape vectors. To overcome the rapid onset of impassable roads, evacuation strategies must also shift toward community-level preparedness. Implementing mutual assistance evacuation models—where community members are pre-assigned to aid vulnerable individuals—can significantly improve the successful pedestrian clearance rate within this critical sub-30-minute window before the routes are inundated.

4.2 Temporary Evacuation Shelter near the Red Zone

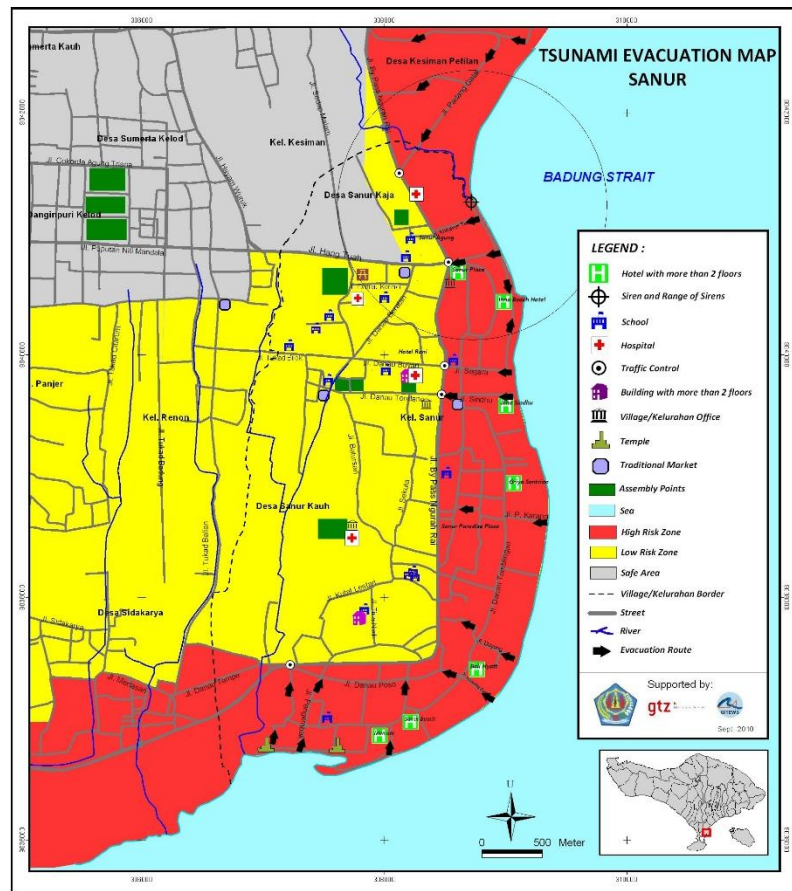


Figure 11 - Existing Tsunami Evacuation Shelter in Sanur

To contextualize the hydrodynamic hazard results within practical disaster risk reduction frameworks, it is essential to evaluate the existing evacuation infrastructure in Denpasar City. Figure 11 illustrates the existing Tsunami Evacuation Map for the Sanur region (established in 2010), which outlines the current spatial distribution of evacuation routes, Tsunami Evacuation Shelters (TES), and designated safety zones. Based on the existing map, the region is distinctly partitioned into high-risk (red), low-risk (yellow), and safe (grey) zones, with the high-risk zone encompassing the densely populated and economically critical immediate coastal strip.

The primary horizontal evacuation strategy relies on designated routes that direct populations westward, moving perpendicularly away from the coastline. A critical logistical challenge identified in this spatial layout is the necessity for evacuees to traverse major arterial roadways—most notably Jalan By Pass Ngurah Rai—to successfully transition from the high-risk coastal zones to the inland assembly points situated in designated safe areas (such as Renon

and Sumerta Kelod). The temporal variability of wave arrivals identified in this study's modeling (e.g., maximum amplitudes frequently occurring during the second or third waves) is highly relevant here. If early warnings are rapidly disseminated, this delayed peak amplitude may provide a critical, albeit narrow, time window for populations to execute this horizontal evacuation toward inland assembly points.

However, recognizing the potential time constraints of horizontal evacuation and the dense concentration of coastal populations, the current spatial plan reveals a heavy reliance on vertical evacuation strategies utilizing existing, non-purpose-built infrastructure. The map demonstrates that rather than depending solely on newly constructed, dedicated TES facilities, the region integrates commercial and tourism infrastructure into its evacuation network. Numerous "Hotels with more than 2 floors" and other multi-story commercial buildings are explicitly designated as vertical evacuation hubs directly within the high- and low-risk inundation zones.

This reliance on existing infrastructure highlights the practical value of the high-resolution hazard parameters modeled in this study. For these multi-story hotels to serve as effective TES, they must not only be tall enough to exceed the maximum modeled inundation depths but must also possess sufficient structural integrity to withstand the maximum momentum fluxes generated by the incoming waves. The structural damage likelihoods mapped in this study emphasize the urgent need for structural audits of these specific designated hotels to ensure they can survive the physical forces of the worst-case megathrust scenarios outlined herein (Zhang et al., 2019).

Furthermore, the result of this study marks the expanding "Very High" damage zone in the upper ranking makes it practically impossible for individuals deep within the red zone to reach natural high ground within 25 minutes. Consequently, strategically placing vertical Temporary Evacuation Shelters (TES) throughout the Sanur-Serangan corridor is a non-negotiable requirement (Usman et al., 2024). Optimizing TES placement must balance geographical accessibility, population density, and structural safety to ensure the maximum number of people can reach them before the first wave strikes (Zhang et al., 2019).

4.3 Building Retrofitting for High and Very High Risk

Along the eastern Sanur coastline and southern embayments, the flow velocities generated by extreme scenarios have sufficient momentum to cause widespread structural scouring and building failure. It is vital to implement stringent structural retrofitting for

buildings situated within these High and Very High-risk zones. Coastal vulnerability assessment models indicate that structures must be specifically evaluated for hydrodynamic loads, sea-level rise exacerbation, and wave overtopping, rather than solely for standard seismic loads (Çal & Ciravoğlu, 2024; Quiñones-Bustos et al., 2021).

To diminish the sheer force of the incoming tsunami, retrofitting strategies should also extend to the coastal defense infrastructure itself. Introducing wave-absorbing revetments and recurved walls at the shoreline can force flow separation and significantly increase the drag on solitary waves, effectively reducing the inundation depth and flow velocity before the water reaches the built environment (Lee et al., 2022).

5. Conclusion

The multiple deterministic scenario framework provides a broader range of plausible tsunami hazard conditions than a single deterministic scenario within the scope of this study. By applying a multiple-scenario framework, this study explores a broader range of potential earthquake sources compared to traditional single-scenario assessments, offering a more robust hazard envelope. However, it is recognized that these multi-deterministic projections capture only a portion of the inherent variability in tsunami behavior. Future assessments must consider other significant sources of uncertainty that govern wave generation and propagation, including complex fault rupture characteristics, high-resolution bathymetric and topographic variations, sediment conditions, and localized bottom friction

Simulations of nine M_w 8.7 deterministic rupture scenarios highlight the projected acute temporal and spatial vulnerabilities of the Sanur–Serangan coastal zone. Temporally, the models reveal a consistently narrow evacuation window; wave arrival times generally range from 23 to 38 minutes, regardless of the specific rupture characteristics. Because this study specifically analyzed near-field, maximum-magnitude megathrust ruptures, these rapid arrival times highlight a critical localized vulnerability that differs significantly from far-field tsunami threats.

Spatially, the hazard shows a marked increase at higher ranks. Under extreme (upper-ranking) scenarios, localized coastal geometry and bathymetry amplify both inundation depth and flow velocity, creating continuous high-velocity, highly destructive corridors deep into the built environment. The compounding effect of these hydrodynamic forces drastically expands the area classified as "Very High" for damage likelihood, exposing a vast footprint of critical infrastructure and dense residential zones to catastrophic risk.

Furthermore, in the context of near-field megathrust events originating from the subduction zone directly south of Bali, disaster mitigation strategies in Denpasar shall assume a highly constrained response time of less than 30 minutes. While far-field tsunamis would afford greater lead times, localized community-level preparedness and rapid mutual assistance models remain strictly necessary to ensure successful evacuation during these critical near-field worst-case scenarios. In addition, The hazard maps generated in this study may assist local authorities in prioritizing evacuation planning, temporary evacuation shelter allocation, and infrastructure resilience. Future research should aim to integrate these high-resolution hazard maps with dynamic socio-demographic data to further bridge the modelling to the community level.

Funding Declaration

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Consent to Publish

Not applicable as this research is a single-person work.

Ethics and Consent to Participate

Not applicable.

Author Contribution

This paper is made by single author. Author contributed to the study conception and design. Material preparation, data collection and analysis were performed by Guruh Sukarno Putra. The draft of the manuscript was written by Guruh Sukarno Putra.

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