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The analysis of earthquake and tsunami hazards for the planned development of the Balinese cultural center in Klungkung regency

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Abstract: The planned development of the Bali Cultural Center in Klungkung Regency, Bali, aims to enhance cultural tourism by creating a hub for cultural activities and information dissemination. Given the site's susceptibility to natural hazards, particularly earthquakes and tsunamis, this research assesses the potential risks to ensure safe infrastructure development. The purpose of this study is to analyze earthquake and tsunami hazards through seismic history evaluation and modeling of ground shaking and tsunami propagation. The methodology includes seismic hazard analysis using ShakeMap software for earthquake simulations and tsunami modeling through ComMIT application, providing a comprehensive hazard assessment. Findings indicate that the area is exposed to high seismic risk, with potential shaking intensities reaching VII MMI (353 gal Peak Ground Acceleration) and tsunami inundation heights of up to 6 meters. The study concludes that these results are critical for designing resilient infrastructure and developing effective disaster mitigation strategies. Practical implications include guiding the construction of the Bali Cultural Center with a focus on disaster preparedness and risk reduction, ensuring the safety of both the infrastructure and its occupants.

Keywords: *Balinese cultural center, Cultural tourism, Danger, Earthquake, Tsunami.*

1. Introduction

The Bali Province, a prominent cultural tourism destination, is establishing the Bali Cultural Center (PKB) to showcase its diverse cultures. This center will be located in the Former Excavation Area C downstream of the Unda River watershed in Klungkung Regency, covering an area of 300 hectares. Generally, the Bali Island, holds significant potential but is prone to hazards due to its geographical location at the convergence of the Eurasian Plate and the Indo-Australian Plate. It is also situated between the Asian and Australian continents, and the Pacific and Indian Oceans [8] [9] [10] [11] [12].

The construction of the Bali Cultural Center consists of various infrastructure buildings catering to cultural activities and information dissemination. Each activity can accommodate tens of thousands of people, signifying the need for comprehensive hazards analysis to mitigate potential negative impacts [13] [14].

Based on the tectonic conditions, geography, topography, climate, and historical occurrence of disasters in the Bali Province, particularly within the planned development area of the Bali Cultural Center, there are five potential natural disasters [13]. The potential disasters include earthquake, tsunami, liquefaction, volcanic eruption, and extreme weather [13] [20]. Therefore, this research primarily focuses on analyzing earthquake and tsunami, as both hazards often coincide [15] and pose the highest risk compared to others. [11]. Mitigating the impact of earthquake covers the

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analysis of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) to assess structural building performance [7]. Similarly, determining the height and inundation of tsunami is crucial for guiding mitigation efforts [16] [17] [18]. The analysis serves several benefits, including (1) as a basis for designing infrastructure and organizing the environment of the Bali Cultural Center with a disaster mitigation focus for human safety, and (2) as a foundation for the public to develop practical preparedness actions, particularly evacuation plans and decision-making in residential areas.

2. Research Methods

2.1. Research Location

The planned development site for the Bali Cultural Center was located administratively within the Klungkung Regency, the Bali Province. Specifically, it covered two sub-districts, including Klungkung and Dawan. The coordinates of the site were 8°32'41.35" - 8°34'30.94" South Latitude and 115°24'54.92" - 115°26'6.99" East Longitude, as shown in Figure 1.

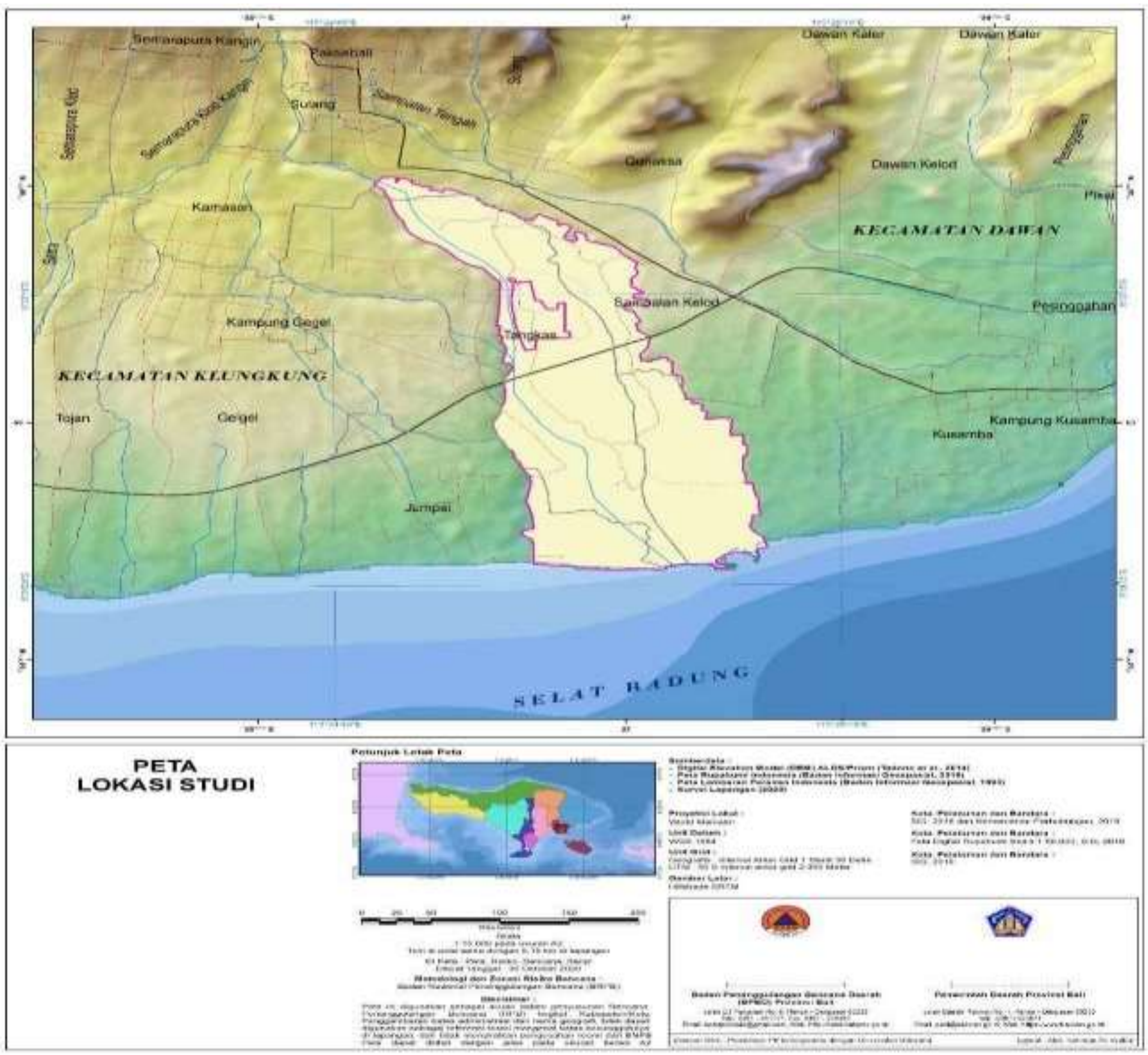

Figure 1.
Location map of the Bali cultural center development plan.

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2.1. Earthquake Shakemap

In assessing the potential of earthquake hazards, earthquake shaking map (shakemap) served as valuable input for building design. It provided information on maximum ground acceleration and deterministic shaking levels in a specific area following earthquake event. In this research, the shaking map was generated using the Shakemap software developed by the United States Geological Survey (USGS) [1]. It calculated the Modified Mercalli Intensity (MMI) scale post-earthquake, based on ground motion modeling using parameters such as magnitude, location, and earthquake source depth and type.

$$MMI = 0.46MMA + 0.52MMV \quad (1)$$

$$MMI = (MMA + MMV)/2 \quad (2)$$

The ground-shaking values were correlated with the impact of earthquake, expressed by the MMI scale. This showed that higher PGA and PGV values corresponded to greater MMI value. Equation (1) presented the process of determining the MMI value, based on the combination of PGA and PGV values. This could also be simplified to an average earthquake intensity value derived from such parameters, as shown in equation (2). MMA represented the MMI value derived from PGA, and MMV signified earthquake intensity value derived from PGV [2].

2.2. Tsunami Modelling

Tsunami modeling aimed to simulate tsunami events to estimate their impacts and formulate mitigation measures in a specific area. This research categorized the modeling into three main stages.

1. Determination of earthquake-triggered tsunami scenarios. These scenarios formed the basis for modeling changes in the seafloor, which served as input for the initial condition in tsunami modeling. Earthquake scenarios were determined through a literature review, particularly relying on results from the National Earthquake Research Center [3].
2. Tsunami propagation modeling was conducted using the Community Model Interface for Tsunami (ComMIT) application developed by the NOAA Center for Tsunami Research (NCTR). The ComMIT application adopted a numerical strategy called the Method of Splitting Tsunami (MOST), which simulated three stages of evolution, including earthquake generation, trans-oceanic wave propagation, and tsunami inundation on land [4]. Initially, tsunami modeling using ETOPO1 1 arc-minute bathymetry data and topographic data from the CGIAR SRTM 90m digital elevation did not adequately represent the geographical conditions of the Gunaksa Village area. Therefore, additional bathymetry and topographic data, including the SRTM 1 arc-second data provided by USGS (http://earthexplorer.usgs.gov/) and the GEBCO 30 arc-second bathymetry data (https://www.gebco.net/), were used.
3. The inundation map, generated from tsunami wave propagation modeling using the ComMIT application (https://nctr.pmel.noaa.gov/ComMIT/), provided data on the extent of tsunami waves reaching the land area and the depth of flooding. This data was further processed using the Q-GIS application (https://qgis.org/en/site/), which was based on a geographic information system, to facilitate understanding. A potential result of this research was tsunami inundation map for the Bali Cultural Center, which was easy to interpret and could guide building design and environmental management.

3. Results and Discussions

3.1. Seismicity of the Bali Area

Based on the data from BMKG (2006 – 2019) [5] and the International Seismological Center – ISC (1960 – 2014) [6], the level of seismic activity in the Bali regional area over the last 50 years has been quite high with varying magnitudes and depths (Figure 2). The shallow earthquake was primarily concentrated around the southern arc of the islands, the subduction zone, and the geological structure of the Flores Back Arc Thrust. Furthermore, seismic clusters at very shallow depths with epicenters on land were mainly caused by the activity of active faults running from east-northeast to west-southwest from the Bali to the Nusa Tenggara Islands.

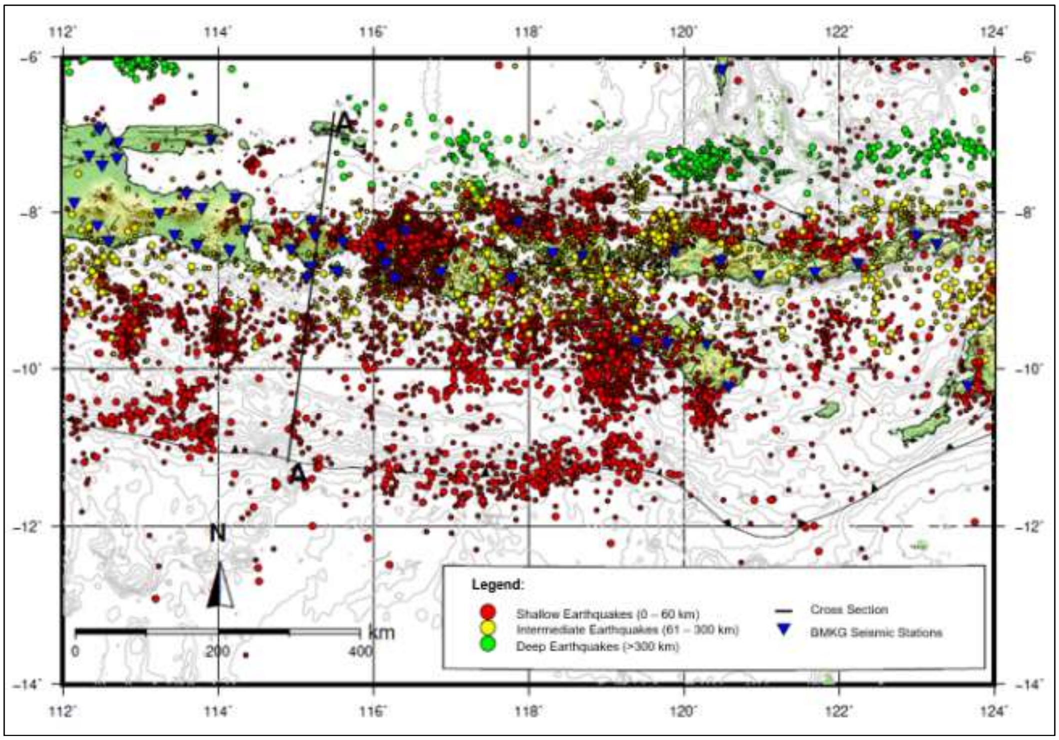

Figure 2.
Bali regional seismicity map for the period 1960-2019.

The cross-section map (Figure 3) showed the distribution pattern of earthquake based on magnitudes and depths. The subduction of the Indo-Australian plate was causing the Eurasian plate to buckle, particularly up to approximately 200 km north of the Bali Island. This was manifested by numerous medium-depth earthquake (depths of 60 – 300 km) around the island arc and deep earthquake (depths > 300 km) occurring north of the arc. Meanwhile, the shallow earthquake around the northern island arc showed seismic activity resulting from the Flores Back Arc Thrust and local faults.

In the planned area of the Bali Cultural Center development, most earthquake were small, with magnitudes less than 5.0, and varying depths ranging from shallow to moderate (Figure 4). The area faced potential damage due to the significant impact of earthquake from several seismic sources in the Bali Province and its surroundings, particularly the Subduction Zone south and Flores Back Arc Thrust north of the Bali). The nearest areas to Klungkung Regency that have experienced significant earthquake sequences were Karangasem, Mount Agung, Seririt–Buleleng, and Lombok.

In addition to earthquake data from the past 50 years, records of damaging earthquake before that period were essential for seismic investigations. According to the Significant and Damaging Earthquake Catalog 1821-2018 by BMKG [17], a damaging earthquake strucked the Klungkung Regency on January 21, 1917. This earthquake, centered southeast of the Bali Island (epicenter point 8.00 LS - 115.90 BT), was accompanied by tsunami reaching 2 meters in height. A map showcasing damaging earthquake occurrences in the Bali Province was presented in Figure 5.

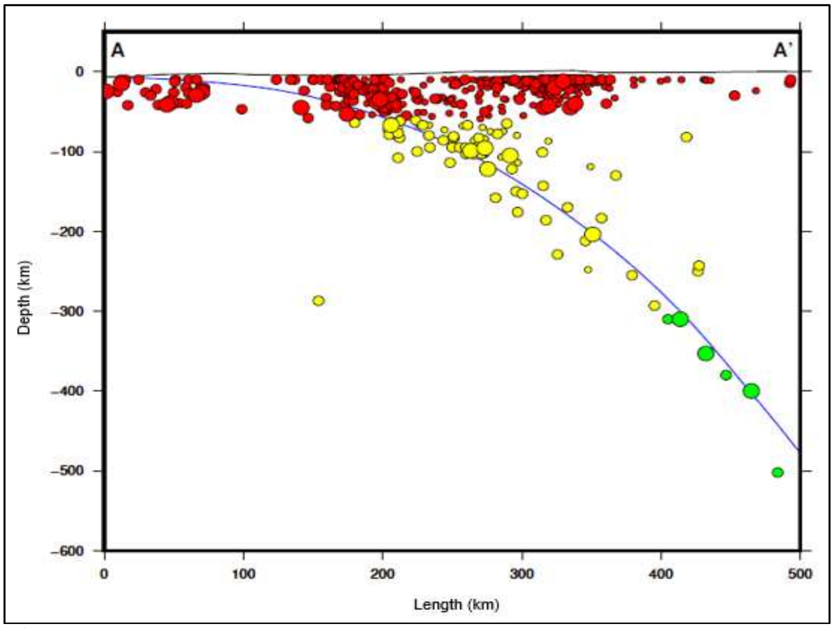

Figure 3.
Regional Cross-Section Map of Bali for the period 1960 – 2019.

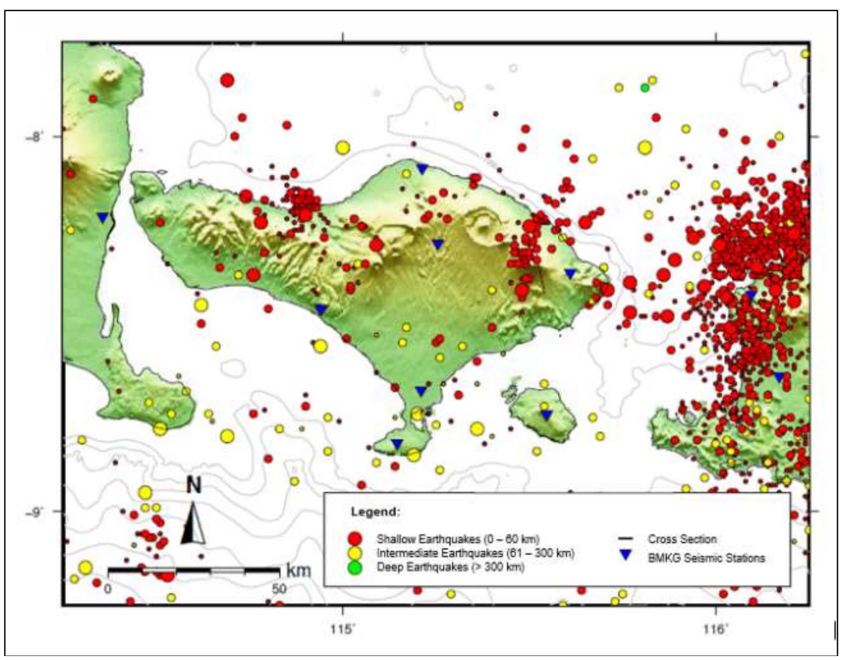

Figure 4.
Seismic map in the Bali region for the period 1960 – 2019.

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3.2. Earthquake Shock Map (ShakeMap)

Based on the 2017 PUSGEN research, there were four potential sources of damaging earthquake around the Bali Province. Two of the sources originated from the subduction activity of the Indo-Australian plate against the Eurasian plate south of the Bali and East Java, with maximum potential magnitudes of M8.5 and M8.7. The third significant earthquake potential was from the north due to the Flores Back Arc Thrust, with a maximum potential magnitude of M7.4. The fourth earthquake potential was originated from the Lombok Strait Strike-Slip North, with a maximum magnitudes of M7.6, as indicated by red stars in Figure 6.

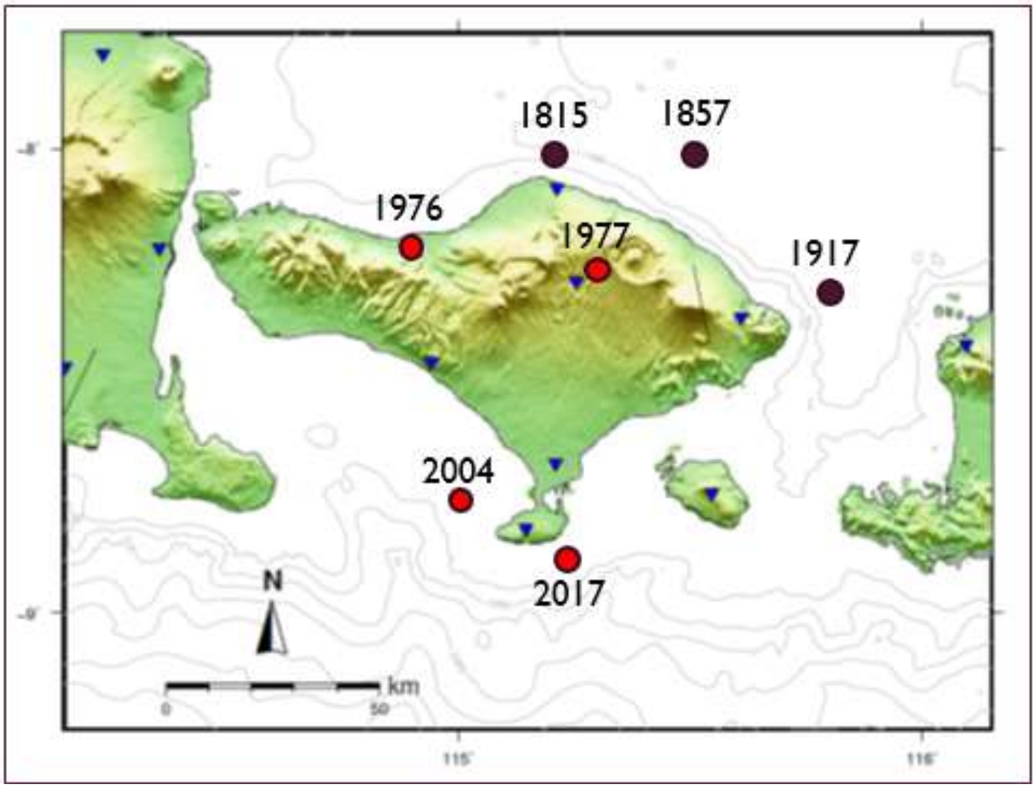

Figure 5.
Map of destructive earthquake in the Bali region for the period 1821-2018

In addition to the potential sources, there have been at least two significant earthquake in the Bali Province during the history of modern seismology. Historical records showed that in 1976, the province experienced a major earthquake causing damage and casualties. According to the catalog at https://www.globalcmt.org/, this was considered a shallow earthquake with a magnitude of Mw 6.5, located in Seririt, North Bali. On December 17, 1979, another damaging earthquake occurred with its epicenter in the Lombok Strait near Karangasem. This was also regarded as a shallow earthquake with a magnitude of Mw 6.5, based on the catalog at https://www.globalcmt.org/ (Figure 5).

Based on the modeling, the M7.6 Lombok Strait earthquake scenario posed the most significant impact on the Bali Cultural Center. Figure 7 presented the level of shaking categorized as Very Strong, equivalent to earthquake intensity of VII MMI. At this intensity, everyone would run outdoors, slight damage would occur to well-built structures, poorly constructed buildings might experience cracks or collapse, chimneys would break, and people driving vehicles would feel the shaking. Table 1 provided the PGA, PGV, and Earthquake Intensity data for the Bali Cultural

Center area based on six significant earthquake scenarios in the Bali Province. According to the table, center could experience shaking levels up to 353 gal or equivalent to 0.36g due to the M7.6 Lombok Strait earthquake.

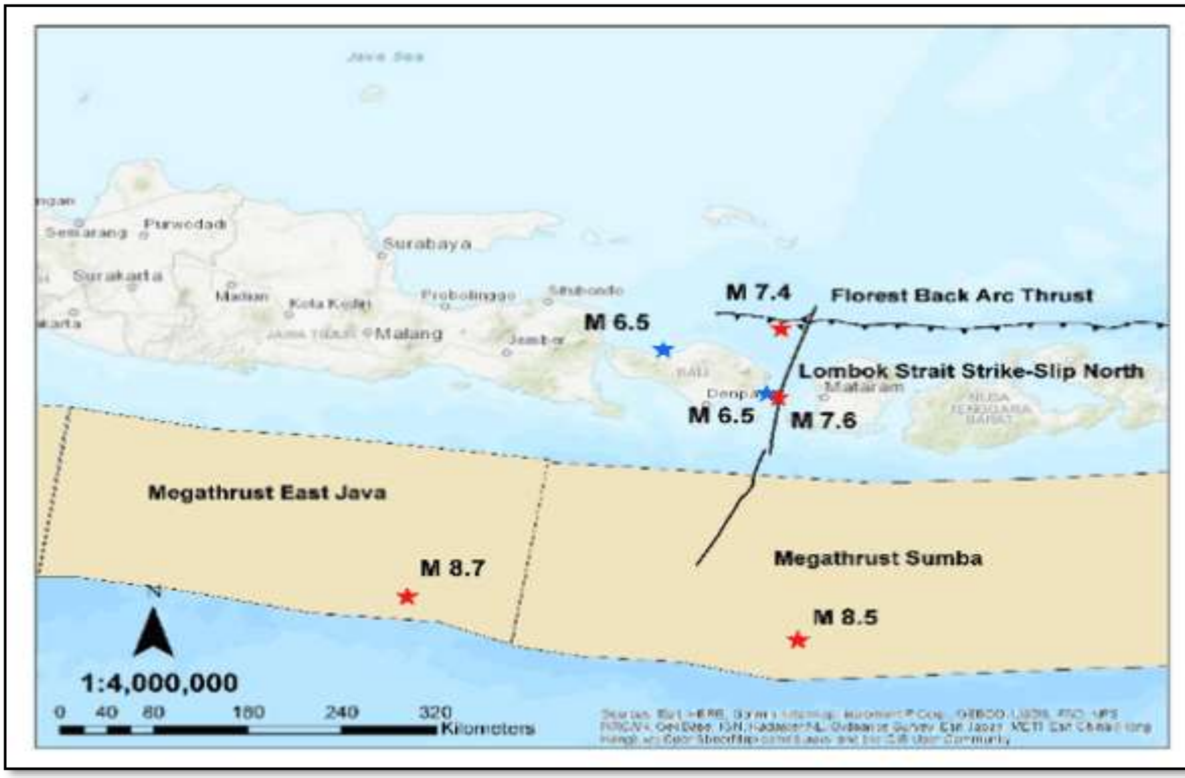

Figure 6.
Epicenter map of the significant earthquake scenarios in the Bali region according to the PUSGEN research [3].

The impact of the other five earthquake scenarios on the Bali Cultural Center area varied from IV MMI, where many people indoors and outdoors would feel the shaking, dishes might break, windows and doors would rattle, and walls would make noise. In the case of VI MMI, everyone would feel the shaking, most people would be startled and run outside, plaster would fall from walls, factory chimneys would be damaged, and minor damage would occur. These scenarios fell within the Moderate to Strong categories.

Table 1.
Ground shaking level in the development area of Bali Cultural Center due to significant earthquake scenarios in the Bali region.

No	Earthquake Parameters				PGA		PGV (cm/s)	MMI	Earthquake source
	Magnitude	Latitude	Longitude	Depth (km)	g	gal			
1	6.5	-8.14	114.89	28	0.08	78.45	4	IV-V	Seririt earthquake, 14/07/1976
2	6.5	-8.54	115.68	15	0.16	156.91	10	V-VI	Karangasem earthquake, 17 /12/1979
3	7.4	-7.95	115.79	10	0.16	156.91	12	VI	Florest Back Arc Thrust
4	7.6	-8.58	115.77	10	0.36	353.04	34	VII	Lombok Strait Strike-slip North
5	8.5	-10.81	115.92	10	0.08	78.45	13	V-VI	Megathrust Sumba
6	8.7	-10.41	112.93	10	0.08	78.45	10	V	Megathrust East Java

Although the M7.6 Lombok Strait earthquake had a smaller magnitude compared to the two megathrust earthquake (M8.5 and M8.7), its impact on the Bali Cultural Center area was significant. This was attributed to the relative proximity of the M7.6 Lombok Strait earthquake's epicenter to the Gunaksa Village area.

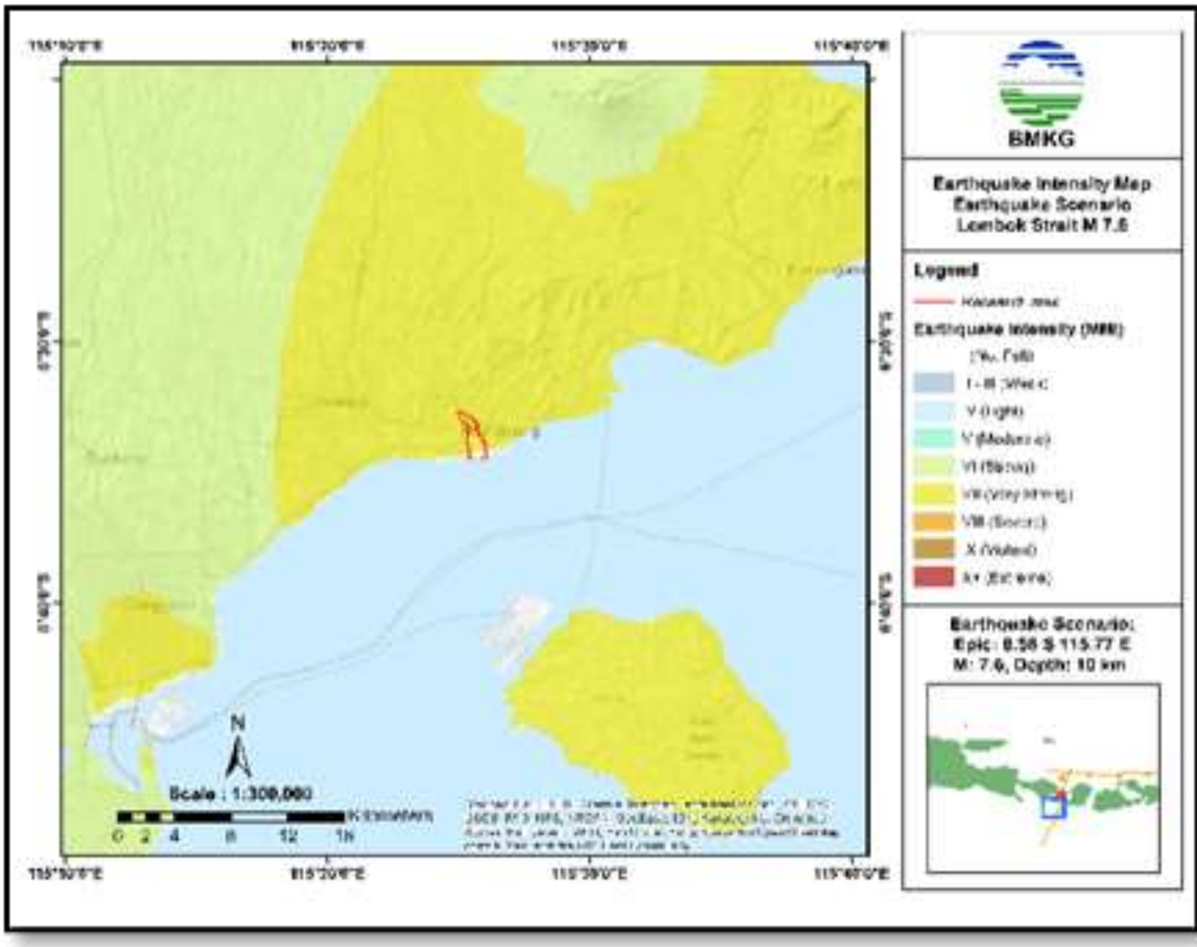

Figure 7.
Intensity map due to Lombok strait earthquake M7.6.

3.3. Tsunami

In examining tsunami potential in the Bali Cultural Center, tsunami modeling was conducted based on two strong earthquake scenarios in South and East Java, attributed to the subduction activity of the Indo-Australian plate beneath the Eurasian plate. These scenarios were derived from PUSGEN research, which suggested that potential earthquake in the Sumba Megathrust segment could reach a magnitude of M8.5, while those in the East Java Megathrust segment reached M8.7 (Figure 6) [3].

3.3.1. Sumba Megathrust Earthquake M 8.5

Tsunami modeling results for the Sumba Megathrust earthquake M8.5 showed that the Bali Cultural Center fell within tsunami-affected area (Figure 8). This inundation map was created by combining eight scenarios with variations in the location and proportion of ocean floor deformation. According to the modeling results, tsunami inundation depths from the ground surface (flow depth) could reach up to 6.8 meters, particularly in the western coastal area. Within Cultural Center area, the inundation depths could reach up to 4 meters.

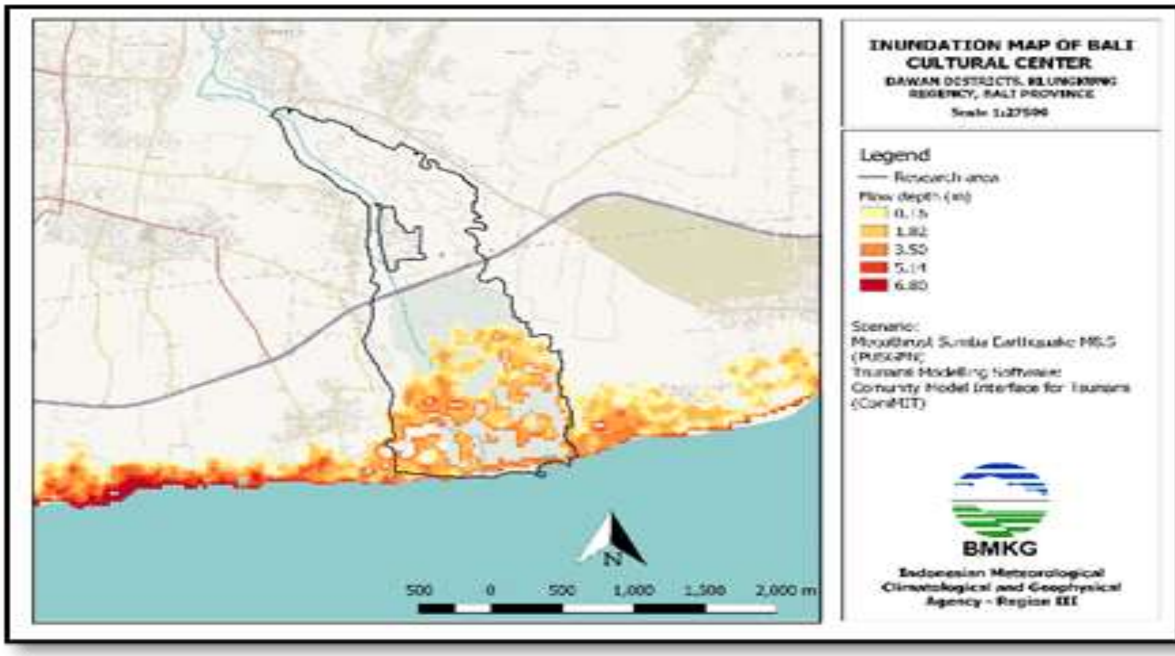

Figure 8.
Inundation map due to Sumba megathrust earthquake M8.5.

By installing artificial tide gauges at four points along the coast in the Bali Cultural Center and its surroundings, as shown in Figure 9, tsunami wave profiles from the eight scenarios could be recorded. The mareograms from tsunami modeling conducted by these artificial tide gauges showed that tsunami wave heights reaching the coastline in the area could range from 3-6 meters (Figure 10).

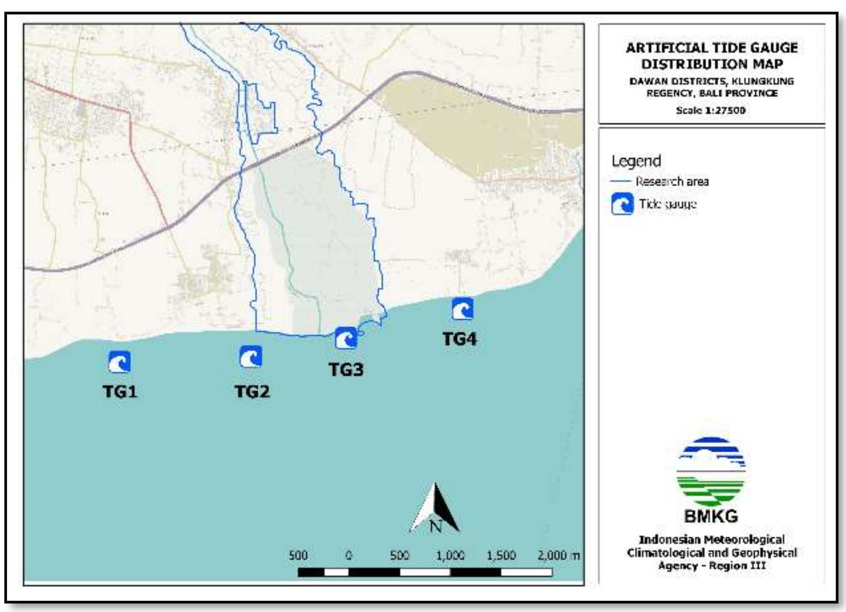

Figure 9.
Artificial tide gauge distribution map.

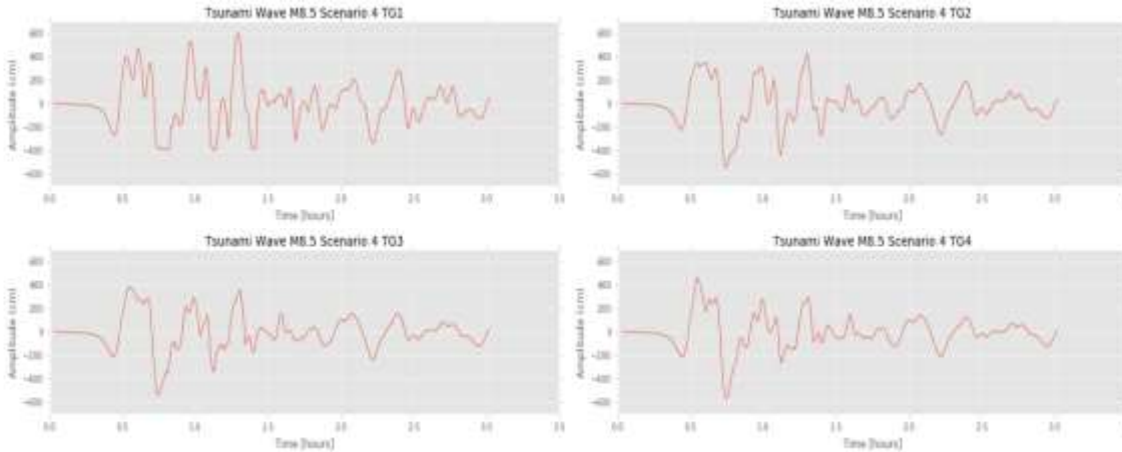

Figure 10.
Artificial tsunami wave records at the coastal area based on scenario 4.

3.3.2. East Java Megathrust Earthquake M 8.7

Similar to the Sumba Megathrust earthquake M8.5, tsunami modeling results showed that the Bali Cultural Center fell within tsunami-affected area due to the East Java Megathrust earthquake M8.7. Figure 11 provided the inundation area and the estimated tsunami inundation height (flow depth) in center and its surroundings resulting from the East Java earthquake. When compared with the previous scenario, the inundation map of the Bali Cultural Center due to the East Java Megathrust earthquake M8.7 was derived from the combination of four scenarios with variations in location and proportions of deformation on the ocean floor.

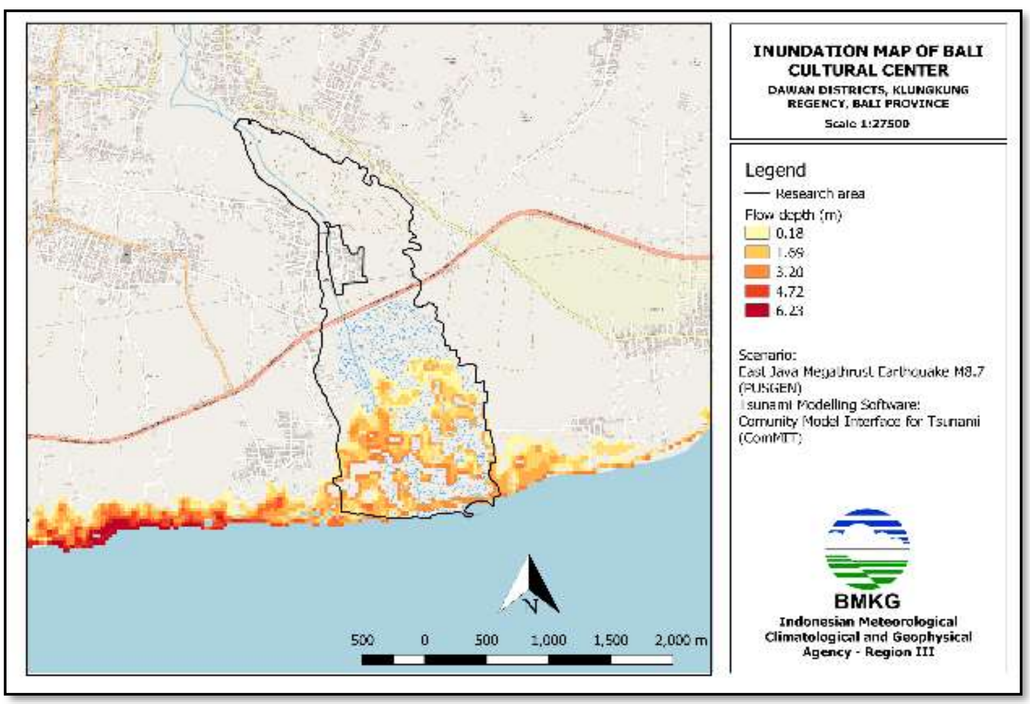

Figure 11.
Inundation map due to East Java Megathrust Earthquake M8.7.

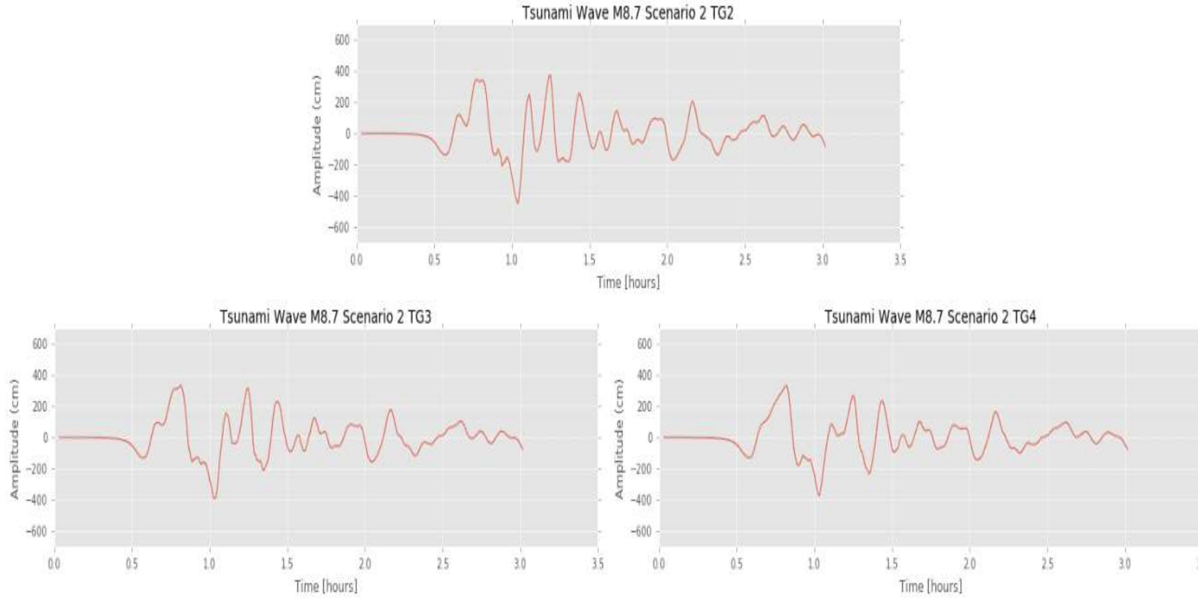

Figure 12.
Artificial tsunami wave records at the coastal area based on scenario 2.

Comparatively, the impact of tsunami resulting from the East Java Megathrust earthquake M8.7 was slightly less severe than that caused by the Sumba Megathrust earthquake M8.5 (Figures 8 and 11). From the ground level (flow depth), tsunami inundation could reach up to 6.2 meters on the western coastline, with a height of up to 3.7 meters within the Bali Cultural Center. Similar to previous recordings, the results from the artificial tide gauges at four points along the coastline showed that tsunami heights when reached the shoreline ranged between 3-6 meters (Figure 12).

3.3.3. Tsunami Prone Area Bali Cultural Center Area and Surroundings

The combination of the two tsunami models resulting from the Sumba Megathrust M8.5 and East Java Megathrust M8.7 earthquake yielded the worst-case scenario tsunami inundation map for the Bali Cultural Center area, as shown in Figure 13. The maximum inundation height (flow depth) reached 6.8 meters on the western coastline of center, with a depth of 4 meters. This corresponded to probabilistic analysis results for the Bali Island beaches, showing a 10% chance of tsunami exceeding 0.5 meters [10]. Additionally, it was in line with the research on Maximum Tsunami Heights on the Bali Island Based on Potential Tsunami-Generating Earthquake on the Sumba Megathrust Segment [18] and Tsunami Evacuation Map for the South Sanur and Serangan Coastal Areas, Denpasar City, the Bali Province [19].

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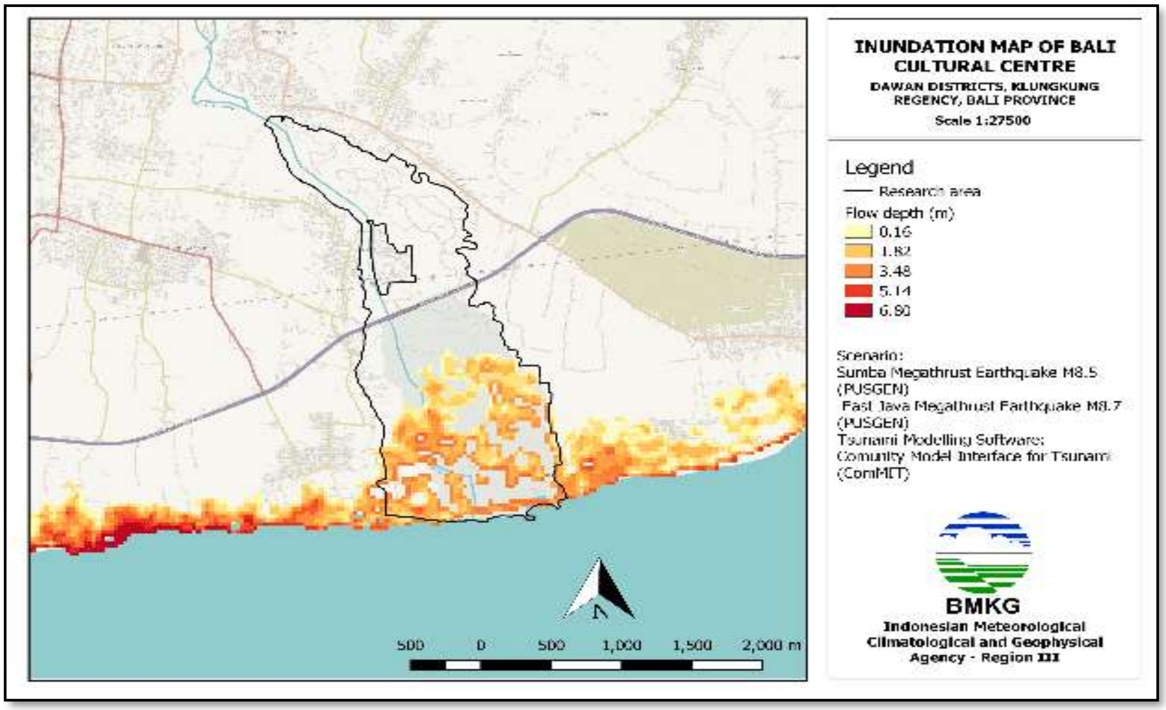

Figure 13.
Composite inundation map due to Sumba Megathrust earthquake M 8.5 and East Java Megathrust earthquake M 8.7.

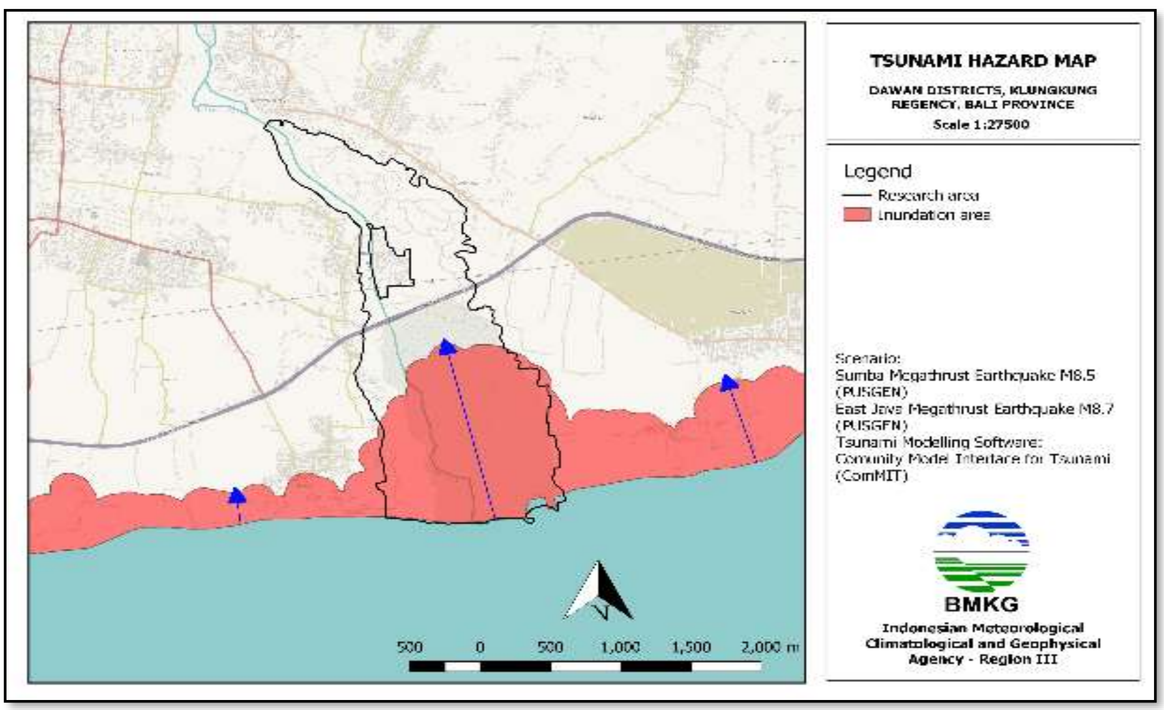

Figure 14.
Tsunami hazards map of Bali Cultural Center area. A blue arrow from left to right is 300 meters, 1500 meters, and 700 meters.

Based on the inundation model, tsunami-prone area map around the Bali Cultural Center was created by adding a 100-meter buffer from the inundation inland area to ensure a safe boundary from tsunami impact. The map model presented in Figure 14 showed that tsunami inundation distance for center could reach up to 1500 meters inland. In comparison, the surrounding areas had an inundation range of only 300-700 meters from the coastline inland.

4. Conclusion and Recommendation

In conclusion, the seismic data from the BMKG Catalog from 1960 to 2019 showed that there were no records of significant earthquake in the Bali Cultural Center, Klungkung Regency. However, it was important to consider the potential impact of earthquake occurring in neighboring regions. Specifically, seismic events have been documented in nearby areas such as Karangasem, Gunung Agung, Seririt-Buleleng, and Lombok. Based on the six simulated earthquake scenarios, the level of ground shaking in the Bali Cultural Center, in accordance with the PGA model, could reach 353 gal or 0.36g. The PGV model indicated ground speeds of up to 34 cm/s, with an earthquake intensity reaching VII MMI, categorized as Very Strong shaking.

Tsunami modeling results showed that tsunami inundation depths near the coastal area of the Bali Cultural Center could reach 4 meters, with a height at the shoreline ranging from 3 to 6 meters. In the Gunaksa Village, the inundation extended up to 1500 meters inland, compared to the surrounding areas, which only reached 300-700 meters inland. This disparity was attributed to the Bali Cultural Center's location within a river basin area.

Further detailed research was recommended to assess disaster risk in the planned development area of the Bali Cultural Center in Klungkung Regency. This investigation should focused on determining the level of disaster risk based on the identified vulnerability level.

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