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Seismic Hazard Assessment in Maluku Province Using PSHA

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ABSTRACT

On 10 January 2023, a strong earthquake with a moment magnitude (M_w) of 7.5 occurred in Banda Sea, Maluku Province. This earthquake caused casualties around the epicentre due to the building collapse which was not an earthquake-resistant structure. A high level of seismic vulnerability and non-standard infrastructure often result in large losses when earthquakes occur. Therefore, mapping of earthquake-prone areas needs to be carried out to optimize the mitigation efforts based on Peak Ground Acceleration (PGA) and Spectrum Acceleration (SA) values. In this paper, mitigation efforts are carried out by mapping earthquake-prone areas using Probabilistic Seismic Hazard Analysis (PSHA) which considers the potential of each complex earthquake source in Maluku Province. Input data was obtained from several earthquake catalogues such as Advanced National Seismic System (ANSS), International Seismological Center (ISC), and United States Geological Survey (USGS) which were processed and analyzed using the Matlab, ZMap, and R-CRISIS programs and mapped using the ArcMap program. The results of PSHA show that Maluku Province is a region with varying levels of earthquake vulnerability. The research results show that the distribution hazard value on PGA in Maluku Province reaches 0.02g to 0.48g for a return period of 500 years and 0.04g to 0.79g for a return period of 2,500 years and on SA for periods of 0.20 seconds and 1.00 second reaches 0.04g to 0.89g and 0.01g to 0.22g for a return period of 500 years and 0.07g to 1.48g and 0.02g to 0.35g for a return period of 2,500 years, respectively. The highest level of vulnerability is in the northern region including Seram Island, Way Apu Island and Ambon Island and the lowest level of vulnerability is in the eastern region including Aru Island.

1. Introduction

Indonesia is one of the countries with very large seismic activity. This condition is caused by the meeting of three main plates, including the Eurasia, Indo-Australian, and Pacific Plates as well as several minor plates that form active plate complex networks such as in North Maluku and Central Sulawesi Province. This large seismic activity can cause natural disasters which have occurred in Indonesia in recent years, including the Central Sulawesi earthquake, landslide, tsunami, and liquefaction in 2018, the Mentawai earthquake and tsunami in 2010, the West Sumatra earthquake and landslides in 2009, the Yogyakarta earthquake and liquefaction in 2006, the West Java earthquake and tsunami in 2006, and the Aceh earthquake, tsunami, and liquefaction in 2004.

The United States Geological Survey (USGS) defines an earthquake as a ground shaking caused by a sudden slip on a fault. This event is caused by the movement of tectonic plates that are stuck on their edges due to friction, which process will store strain energy and will be released as waves that cause shaking in the earth's crust. The shaking of the earth's crust can cause important damage to civilian structures and natural disasters such as large earthquakes and tsunamis along plate boundaries [1].

Eastern Indonesia is a region with a high and unique level of earthquake vulnerability, as is the case in Maluku Province. This level of vulnerability and uniqueness is caused by the complex pattern of faults and subduction zones due to the interaction of three main tectonic plates. Based on the earthquake source in Eastern Indonesia, as shown in Figure 1, the interaction resulted in several

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complex strike-slip faults, thrust/back-arc, and subduction, including Timor back-arc, Wetar back-arc, Tolo thrust, East Molucca Sea thrust, Megathrust North Banda Sea, Megathrust South Banda Sea, and Megathrust Timor.

The biggest earthquake event in the last 10 years was the earthquake in the northwest of Maluku Tenggara Barat Region on January 10, 2023, with a moment magnitude (M_w) of 7.5. The earthquake caused by subduction activity in the Banda Sea was located at coordinates latitude 7.37° S and longitude 130.23° E with a depth of 130 km and has a trust fault mechanism.

In general, the islands in Maluku Province have steep topography and long coastlines which have the potential for secondary natural disasters including landslides and tsunamis due to earthquakes. Therefore, research on seismic behaviour is an important effort in mitigating disasters caused by earthquakes.

The seismic behaviour in eastern Indonesia has been extensively researched, such as seismic hazard research on North Maluku Province using Probabilistic Seismic Hazard Analysis (PSHA) [2]. Peak Ground Acceleration (PGA) values in bedrock with a return period of 500 years and 2,500 years were obtained using earthquake catalogues such as the United States Geological Survey (USGS), International Seismological Summary (ISS), International Seismological Center (ISC), Preliminary Determination of Epicenters (PDE), Advanced National Seismic System (ANSS) and Centennial Catalog. From these catalogues, earthquake sources and historical data were obtained which were processed and analyzed using the Matlab, ZMAP and PSHA-USGS programs. This research indicates that the North Maluku Province is an area that is relatively prone to earthquake hazards, especially in the West Halmahera area and indicates The Philippine Plate, Maluku Sea Plate, and Sangihe Plate influenced this condition.

Furthermore, seismic hazard research was also carried out in other areas around Maluku Province, including Sulawesi Province [3], East Nusa Tenggara Province [4], and West Papua Province [5]. The research in Sulawesi Province includes the influence of site amplification which indicates that many cities are located in soft sediment basins which have the potential to amplify ground movements during earthquakes. The research in East Nusa Tenggara Province includes PSHA with recent seismicity conditions, detailed tectonic background, and appropriate ground motion prediction equations which indicates that the seismic hazard has increased compared to conditions in 2018. The research in West Papua Province includes the influence of completeness magnitude (M_c) and b-value parameters on seismic hazard assessment which indicates the possibility of an increase in stress on the earth's crust around the Ransiki-Yapen based on a decreasing trend of *b-value*.

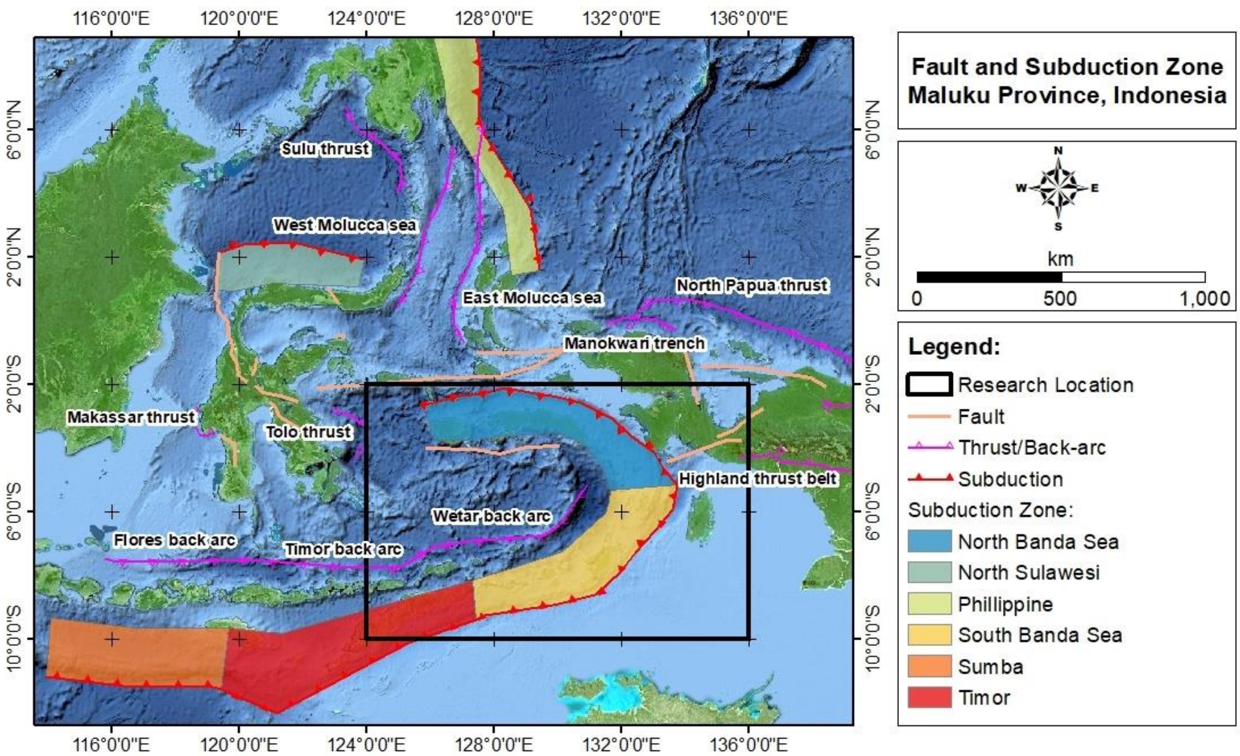

Figure 1 Earthquake source in Eastern Indonesia (modified from [1]).

In this paper, seismic hazard analysis was carried out in Maluku Province using Matlab, ZMap, and R-CRISIS programs to analyze earthquake data and using the ArcMap program to map bedrock acceleration from PSHA results. The purpose of this hazard map is to provide information for mitigation efforts which can be used as a reference in building design, local spatial planning, and developing natural disaster management systems which can reduce losses caused by the impact of seismic disasters. Furthermore, results are expressed both in terms of spectral acceleration for different periods of ground motion which are in bedrock acceleration on PGA and SA for periods of 0.20 seconds and 1.00 seconds with return periods of 500 years and 2,500 years (10% and 2% for periods exceeding 50 years).

2. Methods

This research methodology includes probabilistic seismic hazard analysis using Matlab, Zmap [6], and R-CRISIS programs and seismic hazard mapping using the ArcGIS program. Data preparation is required in the probabilistic seismic hazard analysis, including earthquake sources and historical data to model earthquake source geometries and to calculate earthquake source parameters.

The source and historical earthquake data were obtained from the ANSS, ISC, and USGS catalogues. The data was obtained with a span period from 1900 to 2023, coordinate latitude 6° N to 12° S and longitude 115° E to 140° E, and depth from 0 to 300 km. The seismic data is converted to moment magnitude (M_w) scale from other magnitude types including surface wave magnitude (M_s), body wave magnitude (m_b), energy magnitude (M_E) Richter local magnitude (M_L), and duration magnitude (M_D) using equations in Table 1. The declustering data analysis [7] and the completeness data analysis [8] were carried out to obtain the main and complete earthquake data.

After performing declustering and completeness analysis, the next step is to model earthquake source geometries and calculate earthquake source parameters. The geometry of the earthquake sources is grouped based on the earthquake sources [1] and divided into two shallow layers of depths 0–25 and 25–50 km, two intermediate layers of depths 50–100 and 100–150 km, and two deep layers of depths 150–200 and 200–300 km, respectively. Earthquake data are grouped using the ArcGIS program. After that, the parameters of the earthquake source were calculated using Matlab and ZMap programs to obtain earthquake source parameters for PSHA.

PSHA was carried out using R-CRISIS by including earthquake source geometries and earthquake source parameters. In this step, the attenuation functions and seismic periods are applied to obtain bedrock acceleration values that may occur according to return periods, such as 500 years and 2500 years or probabilities exceeding 10% in 50 years and 2% in 50 years, respectively.

In this paper, the attenuation function is divided into three earthquake sources criteria such as shallow crustal fault and shallow background sources [9] [10] [11] [12] [13] [14], subduction sources [15] [16] [17] [18], and intermediate and deep background sources [16] [15]. After determining the attenuation function, a logic tree method is determined by considering the suitable attenuation model for the research location so that can be considered a credible model without having to choose just one model.

3. Results

In this paper, the research results are divided into two stages such as the results of probabilistic seismic hazard analysis and the results of seismic hazard mapping. The results obtained from probabilistic seismic hazard analysis are bedrock acceleration in grid coordinates and the results obtained from seismic hazard mapping.

Table 1. Conversion magnitude correlation formula for the Indonesia region [19].

Conversion correlation	Number of Data	Range of Magnitude	Consistency (R^2)
$M_w = 0.143{M_s}^2 - 1.051M_s + 7.285$	3,173	$4.5 \le M_s \le 8.6$	93.9%
$M_w = 0.114{m_b}^2 - 0.556m_b + 5.560$	978	$4.9 \le m_b \le 8.2$	72.0%
$M_w = 0.787M_E + 1.537$	154	$5.2 \le M_E \le 7.3$	71.2%
$m_b = 0.125{M_L}^2 - 0.389x + 3.513$	722	$3.0 \le M_L \le 6.2$	56.1%
$M_L = 0.717M_D + 1.003$	384	$3.0 \le M_D \le 5.8$	29.1%

3.1. Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis is carried out to determine the seismic hazard in the Maluku Province. Earthquake sources and historical data obtained from the ANSS, ISC and USGS catalogues amounted to 75,311 earthquake events as initial earthquake data represented in Figure 2.

The declustering analysis [7] was conducted using Matlab and ZMap programs to separate the mainshock earthquake data from foreshock and aftershock earthquake data to obtain 4,810 earthquake events. The completeness analysis [8] was carried out to correct the result of the declustering analysis so that 4,017 earthquake events were obtained as final earthquake data, as shown in Figure 3.

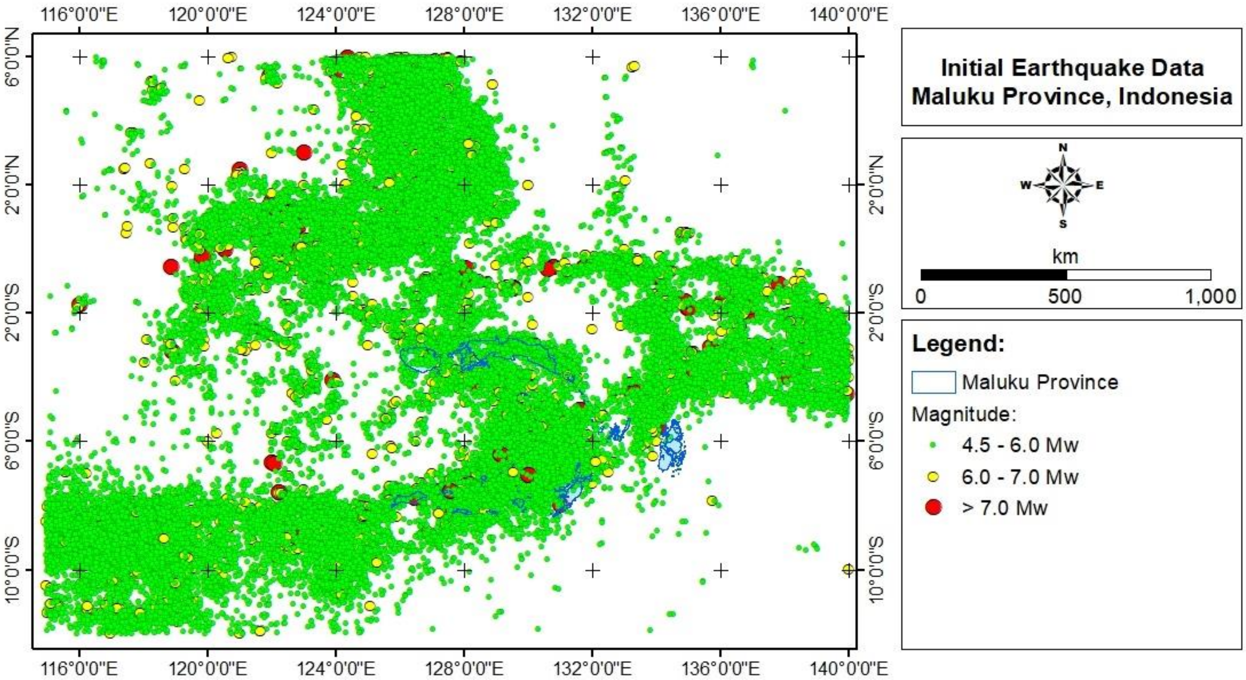

Figure 2. Earthquake data based on ANSS, ISC and USGS catalogues.

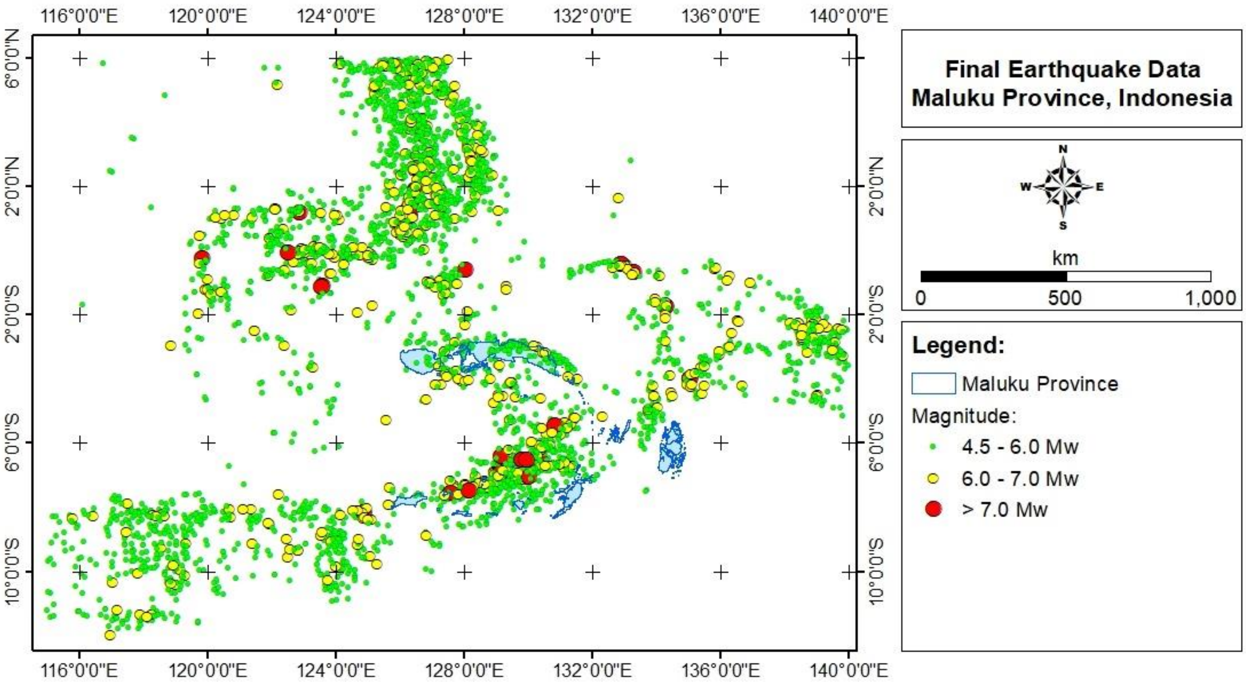

Figure 3. Earthquake data based on declustering and completeness analysis.

The geometry of the earthquake source is obtained based on its depth and location. Earthquake events with a depth of 0 to 50 km and located within the subduction zone are grouped as the subduction source. Earthquake events with a depth of 0 to 50 km but located outside the subduction zone are grouped as shallow background sources. Earthquake events with a depth of 50 to 150 km and 150 to 300 km are grouped as intermediate and deep background sources, respectively. After that, earthquake events can be calculated using Matlab and Zmap programs to obtain the earthquake source parameters, as shown in Table 2.

The probabilistic seismic hazard analysis was carried out using R-CRISIS with attenuation function, as shown in Table 3 and seismic period with 0.00 seconds for PGA as well as 0.20 seconds and 1.00 seconds for SA. In this paper, seismic hazard analysis is carried out with a calculation accuracy of up to 0.2 degrees to obtain the bedrock acceleration value in grid coordinates as in Figure 4.

Table 2. Earthquake source parameters from Matlab and ZMap program.

Source Zone	M_{max}	*a-value*	*a-value annual*	*b-value*	*σ b-value*	*n*	M_{min}	M_c
Subduction								
North Sulawesi	7.80	9.85	8.34	1.48	0.30	64.00	5.41	5.60
Philippine	7.00	10.20	8.67	1.52	0.23	73.00	5.37	5.60
Banda Sea	6.76	12.39	10.85	1.83	0.16	205.00	5.32	5.60
South Banda Sea	6.58	13.93	12.41	2.21	0.36	78.00	5.20	5.60
Timor	6.49	11.04	9.53	1.67	0.16	86.00	5.24	5.50
Sumba	6.30	12.25	10.72	1.87	0.18	102.00	5.10	5.60
Shallow background								
Layer 1 (0-25 m) geometry model 1	7.50	7.38	5.77	0.98	0.10	116.00	5.37	5.50
Layer 1 (0-25 m) geometry model 2	7.70	6.69	5.16	0.84	0.09	145.00	5.30	5.60
Layer 1 (0-25 m) geometry model 3	7.50	8.16	6.64	1.09	0.10	157.00	5.28	5.60
Layer 1 (0-25 m) geometry model 4	7.50	9.78	8.31	1.46	0.27	68.00	5.32	5.60
Layer 2 (25-50 m) geometry model 1	7.00	9.01	7.48	1.22	0.08	240.00	5.24	5.60
Layer 2 (25-50 m) geometry model 2	7.00	9.67	8.10	1.31	0.09	290.00	5.37	5.60
Layer 2 (25-50 m) geometry model 3	7.60	9.03	7.39	1.15	0.05	565.00	5.20	5.60
Intermediate background								
Layer 1 (50-100 m) geometry model 1	7.30	9.34	7.78	1.28	0.08	247.00	5.20	5.50
Layer 1 (50-100 m) geometry model 2	6.20	12.34	10.91	1.94	0.26	48.00	5.30	5.60
Layer 1 (50-100 m) geometry model 3	7.00	11.49	9.93	1.60	0.08	529.00	5.16	5.60
Layer 2 (100-150 m) geometry model 1	7.60	9.88	8.35	1.37	0.10	257.00	5.37	5.60
Layer 2 (100-150 m) geometry model 2	6.67	11.25	9.72	1.60	0.09	297.00	5.10	5.60
Deep background								
Layer 1 (150-200 m) geometry model 1	7.30	10.13	8.53	1.45	0.18	158.00	5.37	5.60
Layer 1 (150-200 m) geometry model 2	6.86	10.48	8.89	1.53	0.16	122.00	5.37	5.60
Layer 2 (200-300 m)	7.40	10.80	9.21	1.57	0.14	169.00	5.20	5.50

Table 3. Attenuation function and probability logic tree (modified from [1]).

Source model	Attenuation Function	Weight
Shallow crustal fault and background sources	Boore and Atkinson (2008) NGA [9]	0.20
	Boore et al. (2014) NGA West-2 [10]	0.20
	Campbell and Bozorgnia (2008) NGA [11]	0.20
	Campbell and Bozorgnia (2014) NGA West-2 [12]	0.20
	Chiou et al. (2008) NGA [13]	0.20
	Chiou and Youngs (2014) NGA [14]	0.20
Subduction sources	Youngs et al. (1997) [15]	0.15
	Atkinson-Boore BC (2003) with Rock & Global Source Subduction [16]	0.15
	Zhao et al. (2006) [17]	0.30
	Abrahamson et al. (2014) BC Hydro [18]	0.40
Intermediate and deep background sources	Atkinson-Boore (2003) with AB Intraslab seismicity Cascadia region BC-rock condition [16]	0.33
	Youngs et al. (1997) with Geomatrix slab seismicity rock [15]	0.33
	Atkinson-Boore (2003) with Intraslab seismicity worldwide data region BC-rock condition [16]	0.33

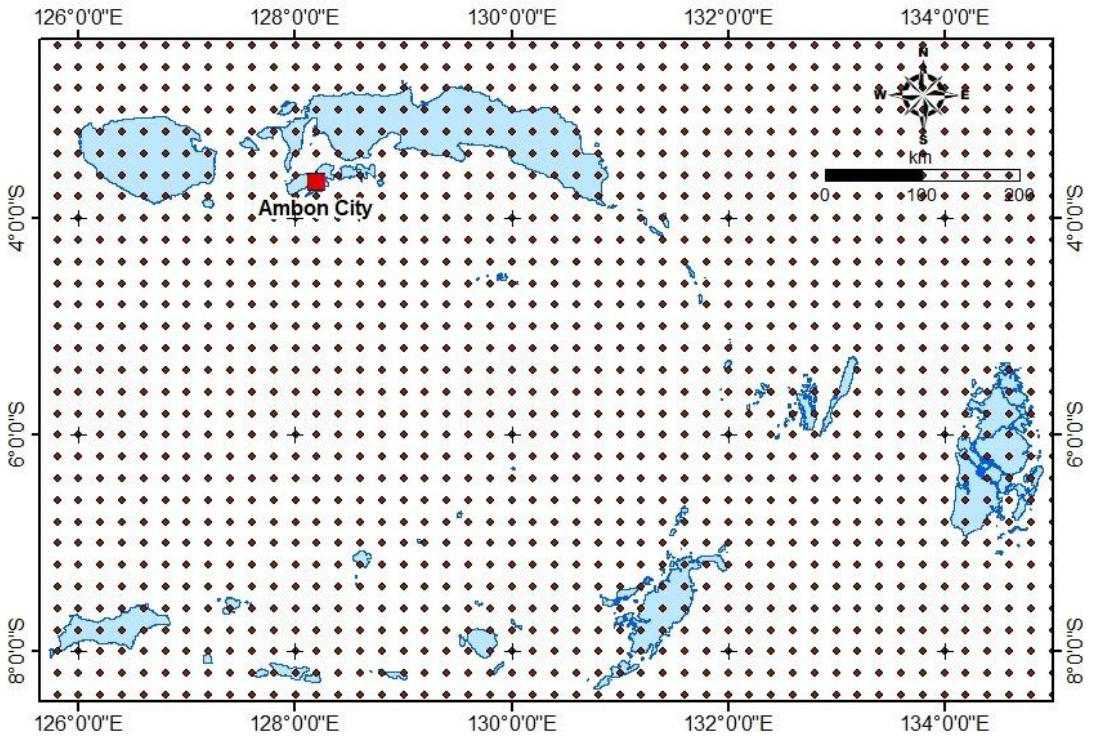

Figure 4. Bedrock acceleration in grid coordinates.

3.2. Seismic Hazard Mapping

The final stage of this research is to map bedrock acceleration from PSHA results which are PGA and SA values in bedrock with a return period of 500 years and 2500 years. Mapping is carried out by analyzing data from the bedrock acceleration in grid coordinates into scale range maps, as shown in Figure 4 and adding some information such as map scale, legends, cardinal directions, coordinate points, and contour lines as in Figure 5.

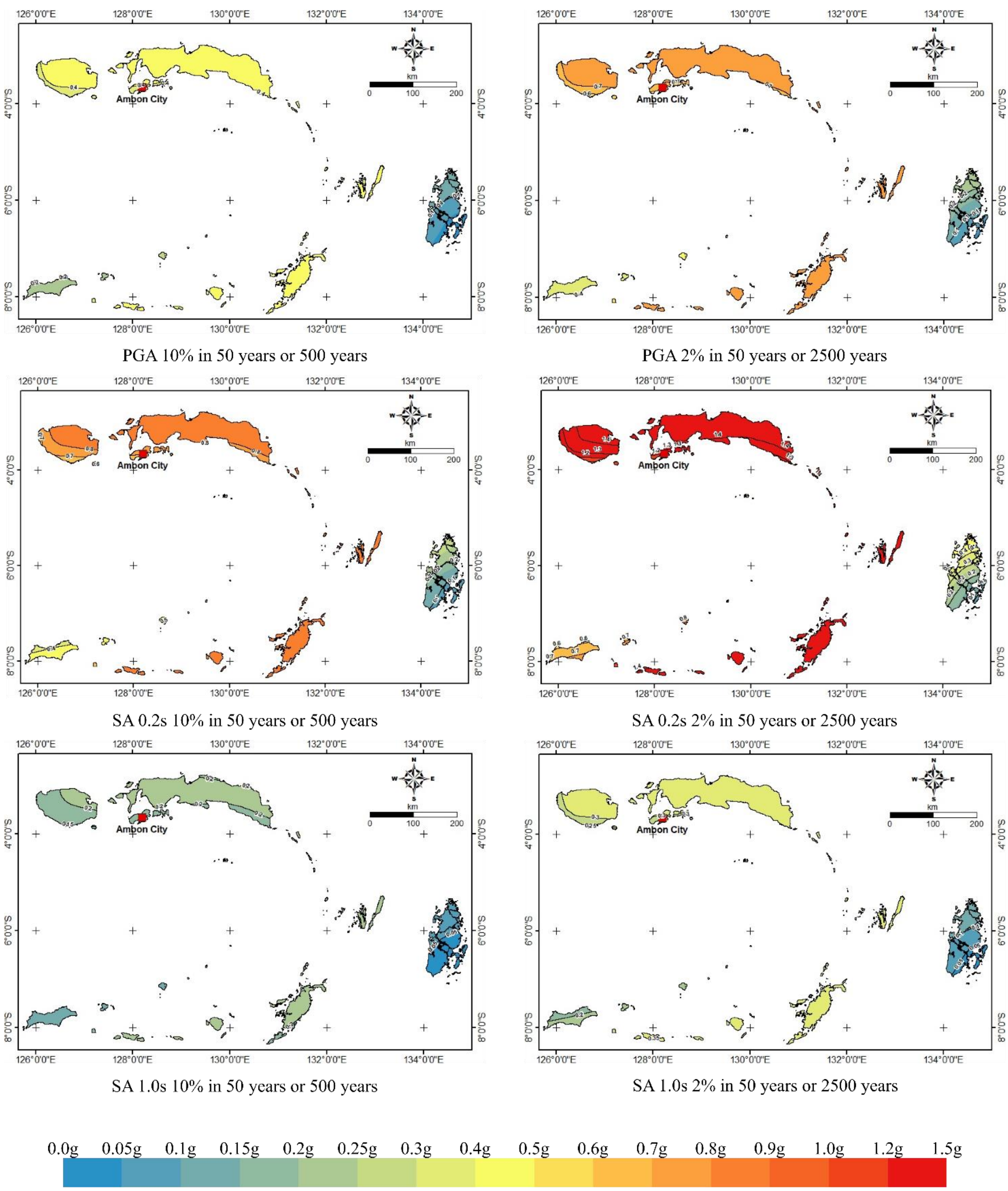

Figure 5. Seismic hazard maps.

At this stage, analysis is carried out using the spline and contour features in the spatial analysis tools in the ArcToolbox menu. The spline feature is used to analyze bedrock acceleration from grid coordinate to scale range, which in this case has a range of 0.05g or 0.30g. The contour feature is used to add information about the contour line between each interval that has been created by the spline feature. Furthermore, the addition of map scale, legends, cardinal direction, coordinate points, and contour line is also given in this stage in the layout view of the view menu.

4. Discussions

The results of the seismic hazard maps on PGA and SA (T=0.20 and 1.00 sec) with return periods of 2,500 years were compared with Indonesia's seismic hazard maps in 2017. Based on Indonesia's seismic hazard maps in 2017, bedrock acceleration with a return period of 2,500 years in Maluku Province on PGA reaches 0.25g to 0.80g and on SA for periods of 0.20 seconds and 1.00 seconds reaches 0.40g to 1.50g and 0.15g to 0.60g, respectively. However, based on this research, the acceleration of bedrock in Maluku Province on PGA reaches 0.02g to 0.48g for a return period of 500 years and 0.04g to 0.79g for a return period of 2,500 years and on SA for periods of 0.20 seconds and 1.00 second reaches 0.04g to 0.89g and 0.01g to 0.22g for a return period of 500 years and 0.07g to 1.48g and 0.02g to 0.35g for a return period of 2,500 years, respectively

From the seismic hazard maps comparison, it was found that there were differences in the results. The differences in results can be caused by several factors such as differences in data sources, data collection time, attenuation function assessment, and justification for earthquake source modelling. Furthermore, differences in the use of the PSHA analysis program also influence the results of the analysis, where the Indonesia seismic hazard maps in 2017 used the PSHA-USGS program and in this paper used the R-CRISIS program.

In this study, various vulnerability analysis results were obtained. The northern region of Maluku Province has a higher level of vulnerability because it is located in earthquake sources caused by the meeting of three main plates such as the Eurasian, Indo-Australian, and Pacific Plates which form an active plate complex [20]. This is indicated by the PGA value for return periods 500 years and 2500 years in northern regions of Maluku are 0.30g to 0.40g and 0.50g to 0.70g, respectively. The eastern region of Maluku Province has a lower level of vulnerability because it is located quite far from earthquake sources such as active faults, thrusts/back-arcs, and subduction zones. This is indicated by the PGA value for return periods 500 years and 2500 years in eastern regions of Maluku are 0.00g to 0.10g and 0.05g to 0.20g, respectively.

5. Conclusions

The result of seismic hazard maps shows that the Maluku Province has varying levels of earthquake vulnerability. The highest level of vulnerability is in the northern region such as Seram Island, Way Apu Island and Ambon Island and the lowest level of vulnerability is in the eastern region such as Aru Island.

This research was conducted to mitigate the impact of seismic disasters by providing actual information regarding the level of vulnerability of Maluku province using the R-CRISIS program which is expected to minimize casualties, infrastructure losses, environmental damage and humanitarian impact. From this research, it was found that the R-CRISIS program can be used well to map seismic hazards using the PSHA methods.

In addition, the deaggregation research can be carried out to develop this research further so that a more informative map is obtained related to the controlling magnitudes and distances for particular return periods of earthquakes [21]. The research on earthquake source characteristic data and attenuation relationships considering the local site effects can be studied in more detail to obtain a vulnerability map with more factual and actual results according to accurate and current conditions [22] [23]. Furthermore, comparative research between probabilistic hazard and deterministic hazard methods can be carried out to obtain comprehensive results to describe the seismic conditions at the research location [24].

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