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Assessment of Bedrock PGA Values based on Probabilistic Seismic Hazard Analysis in Purworejo, Indonesia

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Abstract

Purworejo Regency, Central Java, is directly adjacent to the Indian Ocean in the South, where there is a subduction zone between the Indo-Australian Plate and the Eurasian Plate. The movement of these plates has the potential to cause earthquakes, so for mitigation purposes with the design of earthquake-resistant buildings, PGA analysis and Earthquake Hazard Curve are needed. Data is sourced from the 2017 Indonesian Earthquake Hazard Source Map Book using Hazard Analysis software (USGS PSHA) GMPE modified. The attenuation function or GMPE (Ground Motion Prediction Equation) used is also the same as that used to create the Indonesian Earthquake Hazard Map of earthquake source mechanisms consisting of subduction, fault, and background earthquake with a return period of five hundred, one thousand, two thousand and five hundred, five thousand, ten thousand years. The results show that for a 2500-year return period, the most contributing earthquake source in the Purworejo Regency is a subduction earthquake source, with Kaligesing Subdistrict having the highest PGA value of 0.209 g and Bruno Subdistrict owning the lowest PGA at 0.186 g. The distribution of PGA values at this return period shows that the PGA values increase as the location approaches the subduction earthquake source from North (0.15 – 0.20 g) to South (0.20 – 0.25 g). Based on the PGA value, the Purworejo Regency area could feel the occurrence of earthquake vibrations. However, it is still necessary to mitigate the occurrence of earthquakes by building earthquake-resistant buildings to minimize losses when a major earthquake occurs in the future.

1. Introduction

Purworejo Regency, Central Java, is geographically located 109°47’28’’ - 110°8’20’’ E and 7°32’’ - 7°52’’ S, about± 63 km from the city center of Yogyakarta to the west or ± 38 km from UNESCO cultural heritage site, Borobudur Temple to the southwest. Purworejo district is bordered on the north by the Magelang and Wonosobo districts, on the south by the Indian Ocean, on the east by Kulonprogo district, and on the west by the Kebumen district (Figure 1). The area of Purworejo District is directly adjacent to the Indian Ocean where there is an active subduction zone between the Indo-Australian plate and the Eurasian Plate and is near the active Merapi Merbabu fault in the Northeast (slip rate: 0.1 mm/yr) and the Opak Fault in the East (slip rate 0.75 mm/yr) (PuSGeN, 2017; Abdalla et al., 2024). Both of these faults have a potential magnitude of 6.6 (Murjaya et al., 2021; Prasetyo, 2017). Consequently, the Purworejo Regency area is highly vulnerable to earthquake-induced ground shaking.

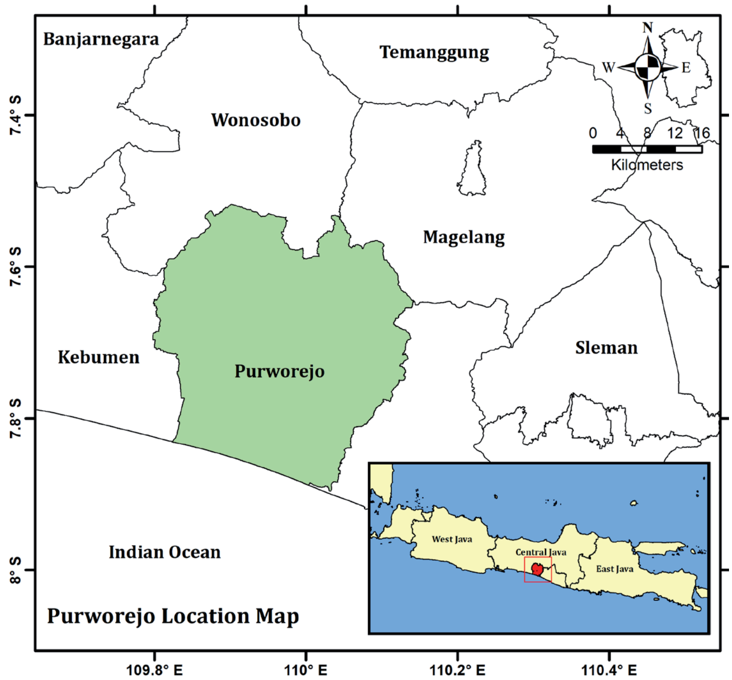


Figure 1. Location of Research Area

This region has experienced an earthquake on July 18, 2016 with a magnitude of 3.6 with a scale of I - II MMI (Wibowo & Nurhaci, 2017; Zainun et al., 2020). There was not any damage or loss reported due to the earthquake. Nevertheless, mitigation efforts due to future earthquakes are required to minimize risks. We applied the Probabilistic Seismic Hazard Analysis (PSHA) method, which considers the potential seismic sources, the random nature of earthquake events, the random nature of ground motions generated by earthquakes, the potential for ground motion damage, and the uncertainties involved at all levels of the process.

Probability is useful in characterizing seismic hazards because earthquakes and their effects are random phenomena. The PSHA method has previously been used in calculating the PGA as reported by Syahbana et al. (2023) for the Lembang Fault and Sari et al. (2020) for Bandung City. This study aims to analyze the distribution of PGA values on bedrock in the Purworejo Regency area using Probabilistic Seismic Hazard Analysis software of USGS PSHA, modified using adopted GMPE that can be applied in Indonesia (PuSGeN, 2017; Sari & Fakhrurrozi, 2020) based on the data used provided by the National Center for Earthquake Studies (PuSGeN).

2. Data and methods

For PSHA (Probabilistic Seismic Hazard Analysis), the parameters of the earthquake required are source mechanism consisting of subduction, fault, and background earthquake sources obtained from the 2017 Indonesian Earthquake Hazard and Source Map Book (Sari et al., 2020). There are 4 megathrust zones and 22 fault zones covered within a radius of 500 km (Youngs et al., 1997) of the research area, as can be seen in Table 1 and Table 2.

Table 1. List of Subduction Earthquake Source Zones Covering the Study Area (PuSGeN, 2017)

No	Subduction Name	a-value	b-value	M-max
1.	Selat Sunda	5.99	1.15	8.7
2.	*West-Central Java*	5.55	1.08	8.7
3.	*East Java*	5.63	1.08	8.7
4.	Sumba	5.63	1.11	8.5

Table 2. List of Fault Earthquake Source Zones Covering the Study Area (PuSGeN, 2017)

No	Fault Name	Slip- Rate (mm/yr)	Sense	Dip	Top	Bottom	L (km)	Mmax
1.	Cimandiri	0.55	RS	45S	3	18	23	6.7
2.	Nyalindung - Cibeber	0.40	RS	45S	3	18	30	6.5
3.	Rajamandala	0.1	SS	90	3	18	45	6.6
4.	Lembang	2.0	SS	90	3	18	29.5	6.8
5.	Baribis – Subang	0.1	RS	45S	3	18	33	6.5
6.	Baribis – Cirebon 1	0.1	RS	45S	3	18	15	6.5
7.	Baribis – Cirebon 2	0.1	RS	45S	3	18	18	6.5
8.	Baribis – Brebes	0.1	RS	45S	3	18	22	6.5
9.	Baribis – Tegal	0.1	RS	45S	3	18	15	6.5
10.	Baribis – Pekalongan	0.1	RS	45S	3	18	16	6.5
11.	Baribis – Semarang	0.1	RS	45S	3	18	34	6.5
12.	Baribis – Rawapening	0.1	RS	45S	3	18	18	6.5
13.	Baribis – Purwodadi	0.1	RS	45S	3	18	38	6.5
14.	Baribis – Cepu	0.1	RS	45S	3	18	100	6.5
15.	Baribis – Waru	0.05	RS	45S	3	18	64	6.5
16.	Baribis – Surabaya	0.05	RS	45S	3	18	25	6.5
17.	Baribis – Blumbang	0.05	RS	45S	3	18	31	6.5
18.	Ciremai	0.1	SS	45S	3	18	20	6.5
19.	Ajibarang	0.1	SS	90	3	18	20	6.5
20.	Opak	0.75	SS	60E	3	18	45	6.6
21.	Merapi – Merbabu	0.1	SS	90	3	18	28	6.6
22.	Pati	0.1	SS	90	3	18	69	6.5

*RS = Reverse Slip, SS = Stike Slip
* L = Length, Mmax = maximum magnitude, S = South, E = East

The data used in this study comes from the 2017 Indonesian Earthquake Hazard and Source Map. It was analyzed using the Probabilistic Seismic Hazard Analysis (PSHA) method with software from the USGS. The PSHA input file includes several parameters, such as slip rate, fault movement type (sense), fault length, dip angle, depth to the top and bottom of the fault, fault width, and maximum possible earthquake magnitude. The Ground Motion Prediction Equations (GMPEs) used in the analysis are the same as those used for the Indonesian Earthquake Hazard Map—Boore et al. (2014), Campbell & Bozorgnia (2014), and Chiou & Youngs (2014)—each given equal weight (Oktaviani et al., 2023; Syahbana et al., 2023).

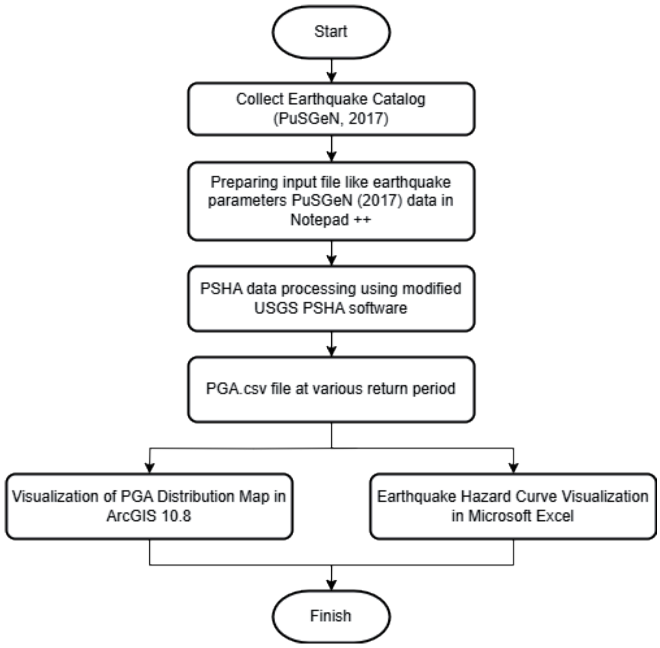


Figure 2. Flowchart of Data Processing.

Data processing was conducted according to Figure 2 and followed the USGS PSHA software algorithm from input to output (Figure 3). Processing for each earthquake source mechanism is carried out separately based on the type of earthquake source, where there are two commands for subduction earthquake sources, three commands for fault earthquake sources and background earthquake sources. Table 3 list the Earthquake Source Mechanism Model and GMPE Weights used in this study.

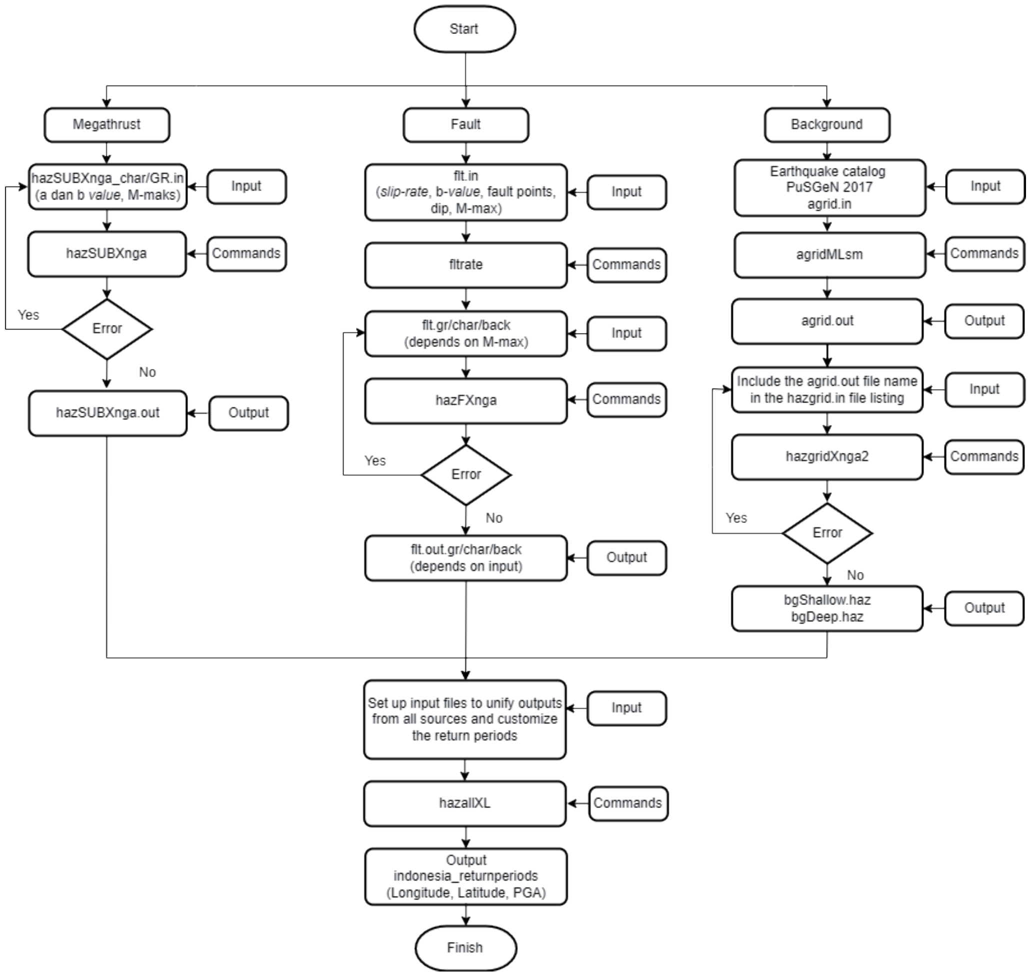


Figure 3. Algorithm Data Processing using Modified USGS PSHA Software.

Table 3. Earthquake Source Mechanism Model and GMPE Weights (Azwar et al., 2022).

Fault Model		
Parameters		Weight (%)
Type	Characteristics	0.66
	Gutenberg Richter	0.34
Magnitude Uncertainty	Mmax -0.1	0.2
	Mmax	0.6
	Mmax +0.1	0.2
GMPE	Boore-Atkinson NGA 2014	0.33
	Cambell-Bozorgnia NGA 2014	0.33
	Chiou-Youngs NGA 2014	0.33
Subduction Model		
Parameters		Weight (%)
Type	Characteristics	0.5
	Gutenberg Richter	0.5
Magnitude Uncertainty	Mmax -0.1	0.2
	Mmax	0.6
	Mmax +0.1	0.2
GMPE	BCHydro 2012 updated	0.33
	Atkinson-Boore 2003	0.33
	Youngs 1997	0.33
Shallow Background Model		
Parameters		Weight (%)
Type	Characteristics	0.66
	Gutenberg Richter	0.34
Magnitude Uncertainty	Strike-Slip	0.33
	Reverse	0.33
	Mmax +0.1	0.33
GMPE	Boore-Atkinson NGA 2014	0.33
	Cambell-Bozorgnia NGA 2014	0.33
	Chiou-Youngs NGA 2014	0.33

Processing of subduction earthquake sources were started with preparing input files to be processed by the command: hazSUBXnga_ed. Next, fault earthquake sources were processed through two commands, fltrate.v2 and hazFXnga7c. Then, background earthquake sources were processed through two commands: agridMLsm.v2 and hazgridXnga2_all2014. The input file of each of these commands contained information from known earthquake source parameters. The results of the hazSUBXnga_ed, hazFXnga7c, and hazgridXnga2_all2014 commands were then reprocessed using the hazallXL.v2 command to obtain information on PGA (Peak Ground Acceleration) values. The output file from the data processing process is a .csv file containing coordinate information and the distribution of PGA values in the research area as (Figure 2).

At the next step, the .csv file, which is the output of the hazallXL.v2 command, was visualized using Arcgis. And the Earthquake Hazard Curve was visualized using Microsoft Excel at various return times in order to determine the maximum ground acceleration values for several return times. This curve was created from the PGA values in seven sample sub-districts. These samples were selected based on the level of population density and the presence of vital infrastructure areas (Table 4).

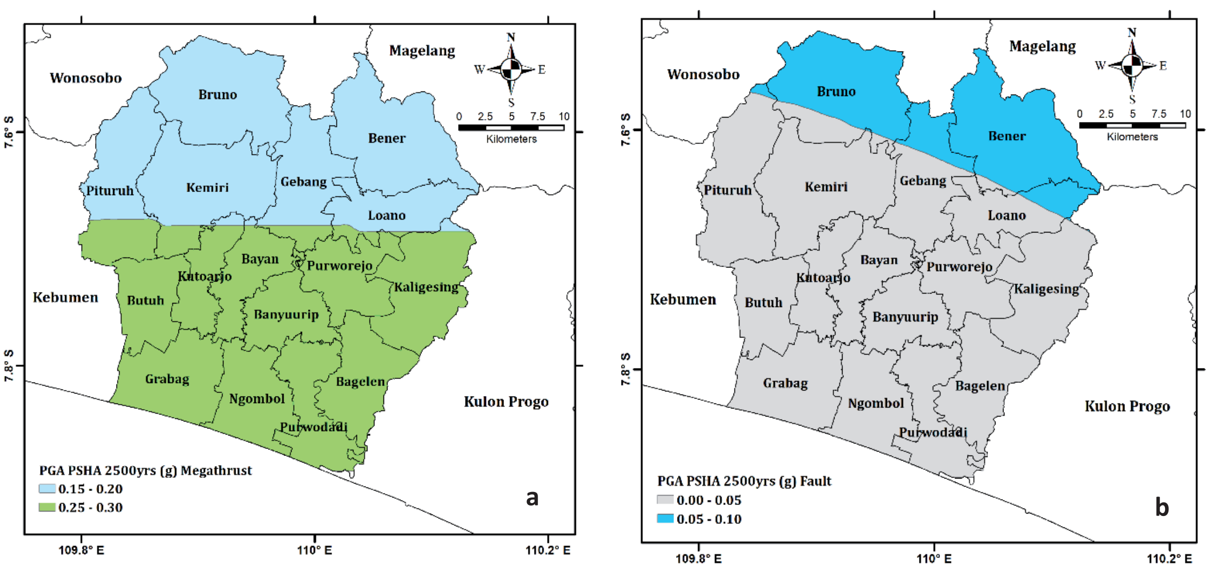
Table 4. Hazard Curve Sample Location Point Purworejo District

No	Location	Longitude	Latitude
1.	Bener sub-district	-7.64°	110.051°
2.	Bruno sub-district	–7.58°	109.92°
3.	Gebang sub-district	-7.65°	109.99°
4.	Kaligesing sub-district	-7.73°	110.08°
5.	Kemiri sub-district	-7.68°	109.89°
6.	Loano sub-district	-7.66°	110.04°
7.	Pituruh sub-district	-7.68°	109.84°

Hazard Curve was created with various return period of 500, 1000, 2500, 5000, 10000 years. The selection of the return period is based on the need to design and retrofit both new and existing infrastructure to withstand seismic hazards.

3. Results and Discussion

The results of calculating PGA values can be seen in Figure 4. The PGA map shows that the earthquake hazard zone at a return period of 2500 years is much influenced by subduction earthquake sources (Figures 4a and 4d) by forming a pattern of higher PGA values to the south, where the location of the subduction zone of the West-Central Java segment is located (0.15 - 0.30 g). The southern coastal areas of Purworejo that are directly close to the zone are the Grabag, Ngombol, and Purwodadi subdistricts. The PGA value depends on the distance and maximum magnitude of the earthquake source. The closer to the earthquake source, the greater the PGA value. The PGA of fault earthquake sources (Figure 4b) has a pattern of getting higher towards the northeast (0.00 - 0.10 g). The reason for this is the presence of the Merapi Merbabu Fault to the northeast and the Opak Fault to the east. Background sources (Figure 4c) have a single PGA value (0.00 - 0.05 g) spread throughout Purworejo Regency.



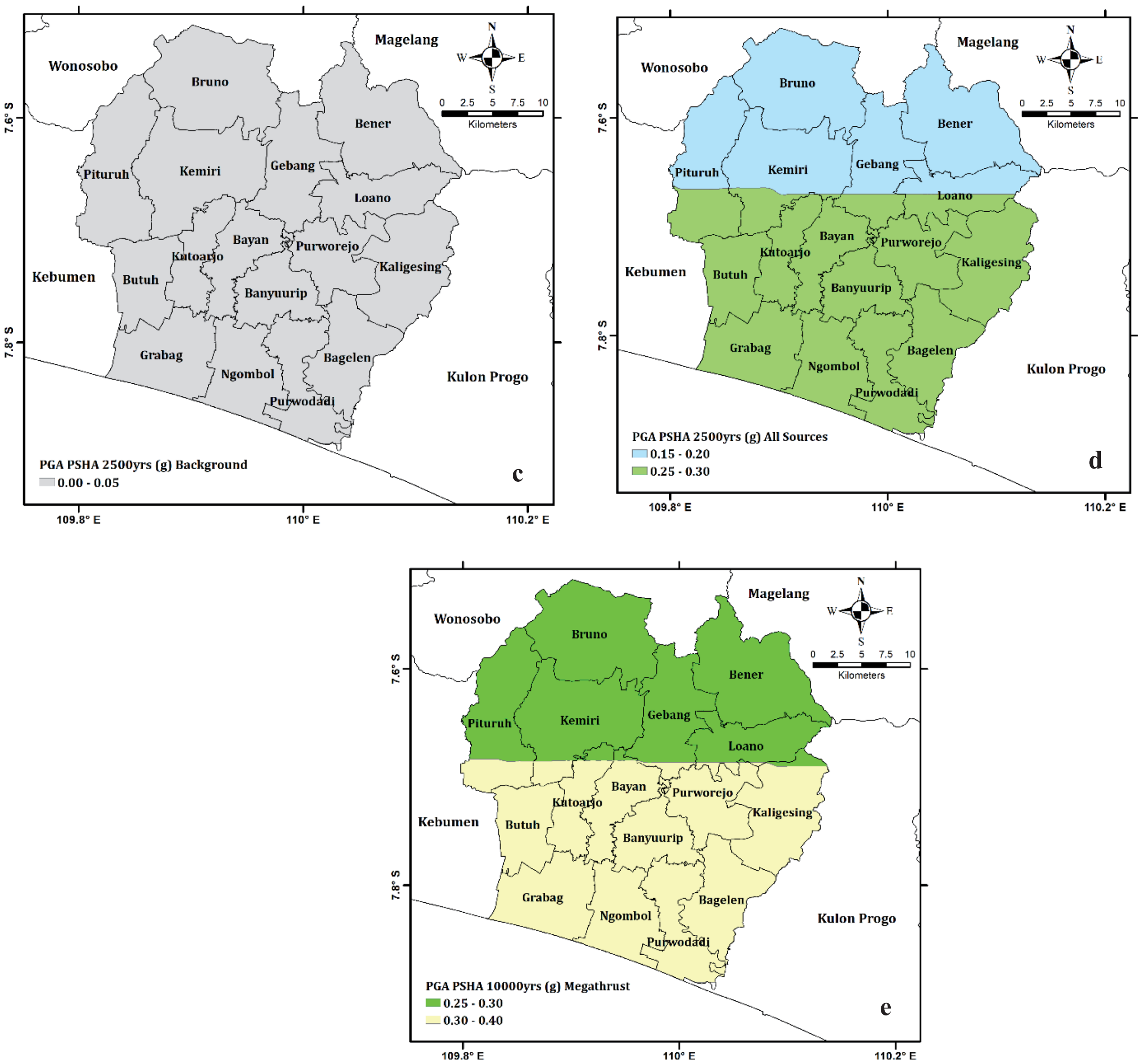


Figure 4. Distribution Map of PGA in Purworejo Regency for a 2500-year return period with various earthquake source mechanisms a) Subduction. b) Fault. c). Background. d) all source mechanisms. e) a 10000-year return periods all source mechanisms.

The effect of earthquake hazards in Purworejo Regency from fault and background earthquake sources is not greater than megathrust sources, because this region rarely experiences earthquakes with large magnitudes. In the catalog of destructive earthquakes from 1821 to 2023, Purworejo district has never experienced any earthquakes that caused damage. This region only feels earthquakes originating from other regions, whereas the magnitude felt ranges from II-IV MMI (Kriswinarso et al., 2024). Based on the results of the analysis of earthquake hazards from megathrust earthquake sources that have a higher impact than other sources, the distribution of PGA values in Purworejo Regency is classified into two zones. The zone is marked in blue on the north side and green on the south side (Figure 4d).

Purworejo district directly faces the subduction zone of the West-Central Java segment. Interestingly, based on new data in the Earthquake Catalog from BMKG, there is a pattern of microearthquake distribution with a NE-SW orientation to the east of Purworejo Regency (Figure 5). That pattern is suspected to be a fault structure, but this assumption has yet to be confirmed. Further investigation is needed to ensure the existence of the suspected structure. The earthquakes in the catalog have depths ≤ 20 km with magnitudes ≤ 4 Mw. Furthermore, the PGA value of the 10,000-year return period PSHA ranges from 0.25 - 0.4 g (Figure 4e) with the pattern getting higher to the south of Purworejo Regency.

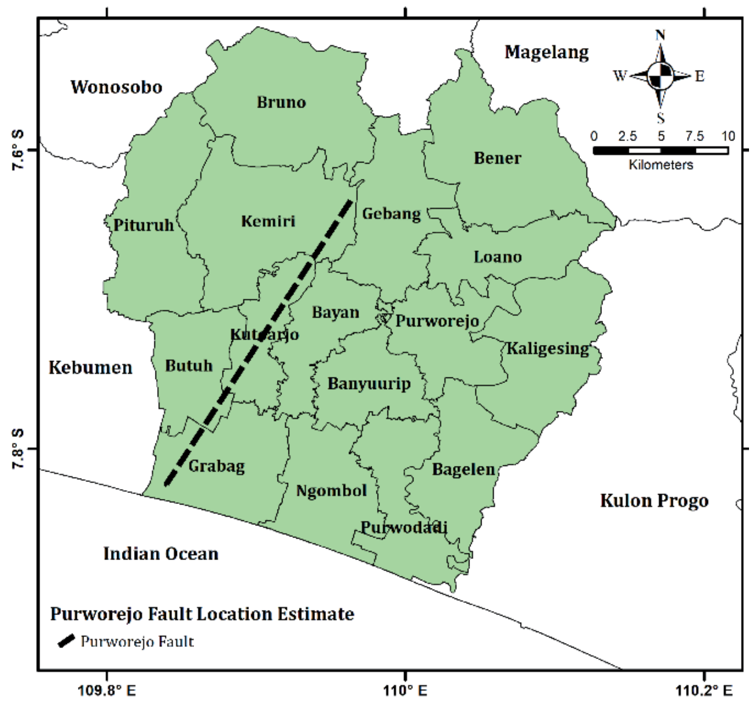


Figure 5. Purworejo Fault Location Estimate from BMKG Catalogue
(Source: Rahmat Triyono Presentation on April 3, 2024)

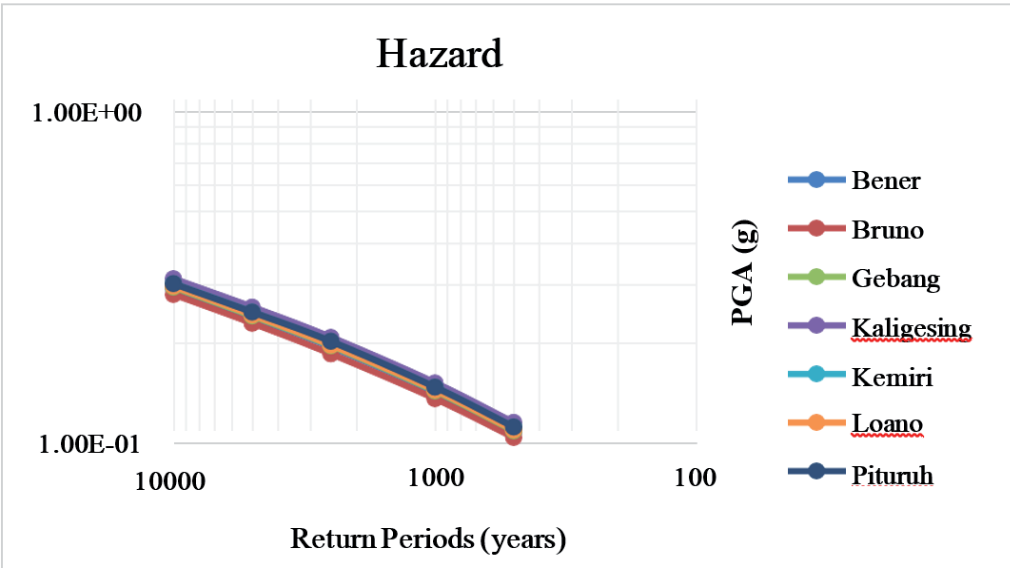


Figure 6. Earthquake Hazard Curve with Horizontal Axis showing the Return Period (Years) and Vertical Axis showing the PGA (g) value. In this curve, it can be seen that the return period of 500, 1000, 2500, 5000, 10000 years in the sample area almost coincides. This means that the earthquake hazards at these return periods are similar.

In addition to reviewing the earthquake hazard map based on PGA, it is also necessary to review the earthquake hazard curve (Figure 6). The curve (Figure 6) indicated that the length of the return period affects the magnitude of the PGA value in an area, where the high PGA value is directly proportional to the longer the return period. At a return period of 2500 years, Kaligesing Subdistrict has the highest PGA value of 0.209 g, followed by Pituruh Subdistrict of 0.203 g, Kemiri Subdistrict of 0.202 g, Loano Subdistrict of 0.198 g, Gebang Subdistrict of 0.197 g, Bener Subdistrict of 0.195 g, and Bruno Subdistrict of 0.186 g. In the Bener District area there is a vital object of the National Strategic Project (PSN), namely the Bener Dam, based on the PGA Map of the 10000-year return period which is the designation of the Dam, the Bener District area has a PGA value of 0.293 g. The results of the PGA value in Purworejo District are appropriate and included in the range <0.29 with a scale of MMI I - II MMI (Wibowo & Nurhaci, 2017)

4. Conclusions

Based on the data analysis and discussion above, it can be concluded that this research produces a PGA map with a return time of 2500 years for subduction, fault, and background earthquake source mechanisms and a return time of 10000 years for all earthquake source mechanisms. Based on the map, the earthquake hazard in Purworejo Regency is dominated by the subduction earthquake mechanism with the PGA value (0.15 - 0.25 g) getting bigger when approaching the earthquake source to the South. Furthermore, based from earthquake hazard curve at a return period of 2500 years, Kaligesing Subdistrict has the highest PGA value of 0.209 g, while based on the PGA Map at a return period of 10000 years which is the designation of the Dam, the Bener Subdistrict area has a PGA value of 0.293 g. Based on the PGA value, it can be concluded that the Purworejo Regency area potentially feel the occurrence of earthquake vibrations although it is still necessary to mitigate the occurrence of earthquakes by building earthquake-resistant buildings to minimize losses when a major earthquake occurs in the future.

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