MULTI-MODEL EVALUATION OF PEAK GROUND ACCELERATION (PGA) FOR SEISMIC HAZARD ZONATION IN NORTH MALUKU, INDONESIA

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ABSTRACT

North Maluku, a region characterized by significant seismic activity, frequently experiences earthquakes that result in various effects, including ground motion. This study evaluates the Peak Ground Acceleration (PGA) values and maps its distribution zones in the North Maluku region using three empirical Ground Motion Prediction Equations (GMPEs): Donovan, McGuire, and Esteva. This research uses a catalog of earthquakes with magnitudes ≥5 and depths <70 km, which occurred in the region between 2010 and 2025. The earthquake data were converted to surface magnitudes and then processed to obtain Peak Ground Acceleration (PGA) values for the three models. The results of each model were then mapped. The results indicate that the Donovan method yields a PGA range of 0.0168g–0.0690g, the McGuire method provides a higher range of 0.0225g–0.0905g, while the Esteva method presents a lower range of 0.0014g–0.0107g. All models consistently identify high-risk zones along the eastern and northern coasts of Halmahera. These variations reflect differences in attenuation behavior, probabilistic assumptions, and depth sensitivity. This demonstrates that spatial consistency across multiple empirical models provides a more reliable and robust basis for seismic hazard zonation than reliance on a single model. The findings highlight the importance of multi-model integration for improving seismic hazard assessment and support the development of more resilient infrastructure and disaster mitigation strategies in seismically active regions.

Keywords: Donovan; Esteva; Maluku; McGuirre; Peak Ground Acceleration (PGA)

Introduction

Indonesia is subject to significant seismic activity due to its position at the intersection of three major tectonic plates: the Indo-Australian, Eurasian, and Pacific plates. The interaction of these plates forms a subduction zone and active faults that stretch extensively from the west to the east of the archipelago.[1] North Maluku, in particular, is at considerable risk of earthquakes due to its location within a microplate convergence zone and its tectonic activity.[2] The frequent earthquakes in this region raise concerns about the safety of infrastructure and communities, especially in densely populated coastal areas. Understanding ground motion characteristics in this region is essential for disaster mitigation and infrastructure resilience.

Peak Ground Acceleration (PGA) is an important metric in seismic studies when assessing earthquake damage. PGA measures ground acceleration during earthquakes and serves as a reference in earthquake-resistant building design. Most regions in Indonesia lack sufficient accelerographs to directly record PGA. As a solution, empirical formulas estimate PGA from earthquake parameters such as magnitude and distance to the source.[3]

Recent international studies emphasize that reliance on a single GMPE introduces uncertainty due to differences in attenuation relationships, tectonic settings, and model assumptions.[4] Multi-model approaches have

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been shown to improve hazard reliability by capturing variability in ground motion prediction.[5]

Most previous studies, however, have focused primarily on numerical PGA estimation rather than on spatial consistency between models, and research in North Maluku remains limited despite its high seismic risk.[6] Therefore, the lack of multi-model comparison studies in North Maluku, and the limited evaluation of spatial agreement between GMPEs and the over-reliance on single-model PGA estimation make this study unique in recognizing spatial consistency across GMPEs as a key indicator of seismic hazard reliability, rather than relying solely on absolute PGA values.[3]

Three commonly used empirical approaches are the Donovan, McGuire, and Esteva models.[7] Donovan's model uses an exponential relationship between earthquake magnitude and distance. McGuire developed a formula that accounts for wave-propagation correction factors, while Esteva's incorporates the influence of depth and the response of surface soil structures to ground acceleration. Each model has its own characteristics and has been widely used in various earthquake hazard mapping studies.[8]

This study employs three distinct models to estimate Peak Ground Acceleration (PGA) values in the North Maluku region, using historical earthquake data sourced from the United States Geological Survey (USGS) catalog. Specifically, each model is applied independently to produce PGA distribution maps. Subsequently, these maps are analyzed to identify areas exhibiting the highest acceleration levels. The resulting estimates serve as a foundation for informed decision-making on regional development and disaster risk mitigation in vulnerable zones.[9]

Based on the above explanation, this study aims to contribute to more precise local seismic zoning.[10] The PGA estimation maps can be valuable tools for local governments, urban planners, and the community at large in developing disaster mitigation strategies and spatial planning that enhance resilience against earthquake risks in North Maluku.

Methods

This PGA research in North Maluku employs the USGS earthquake catalog with the following parameters: magnitude > 5, hypocenter depth < 70 km, and a time frame from June 26, 2010, to July 3, 2025. The study area is defined by the coordinates 2.7° S - 0.93° S and 127.1° E - 128.8° E. All spatial analyses and mapping procedures were conducted using Geographic Information System (GIS) software to ensure consistency in spatial interpolation and visualization. The distribution of earthquake data is shown on the map as in **Figure 1.**

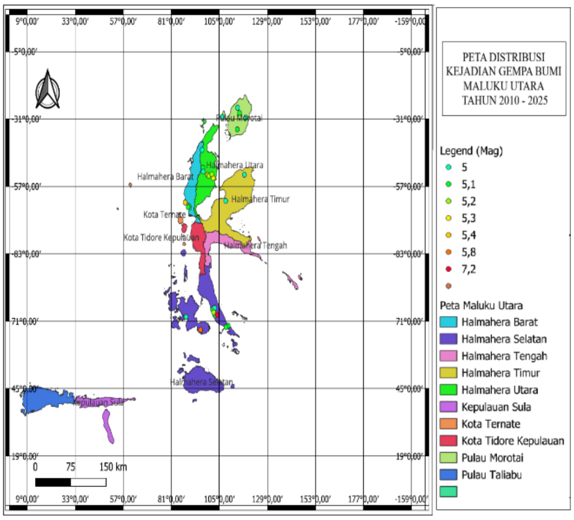

Figure 1. The distribution of earthquakes in Maluku Utara in Juni 2010 – Juli 2025

The methodological framework of this study consists of three principal stages: (1) data processing, which includes data collection, validation, and magnitude conversion; (2) Peak Ground Acceleration (PGA) estimation using empirical models; and (3) spatial analysis to map and evaluate the distribution of seismic hazard. The overall workflow of these stages is illustrated schematically in **Figure 2.**

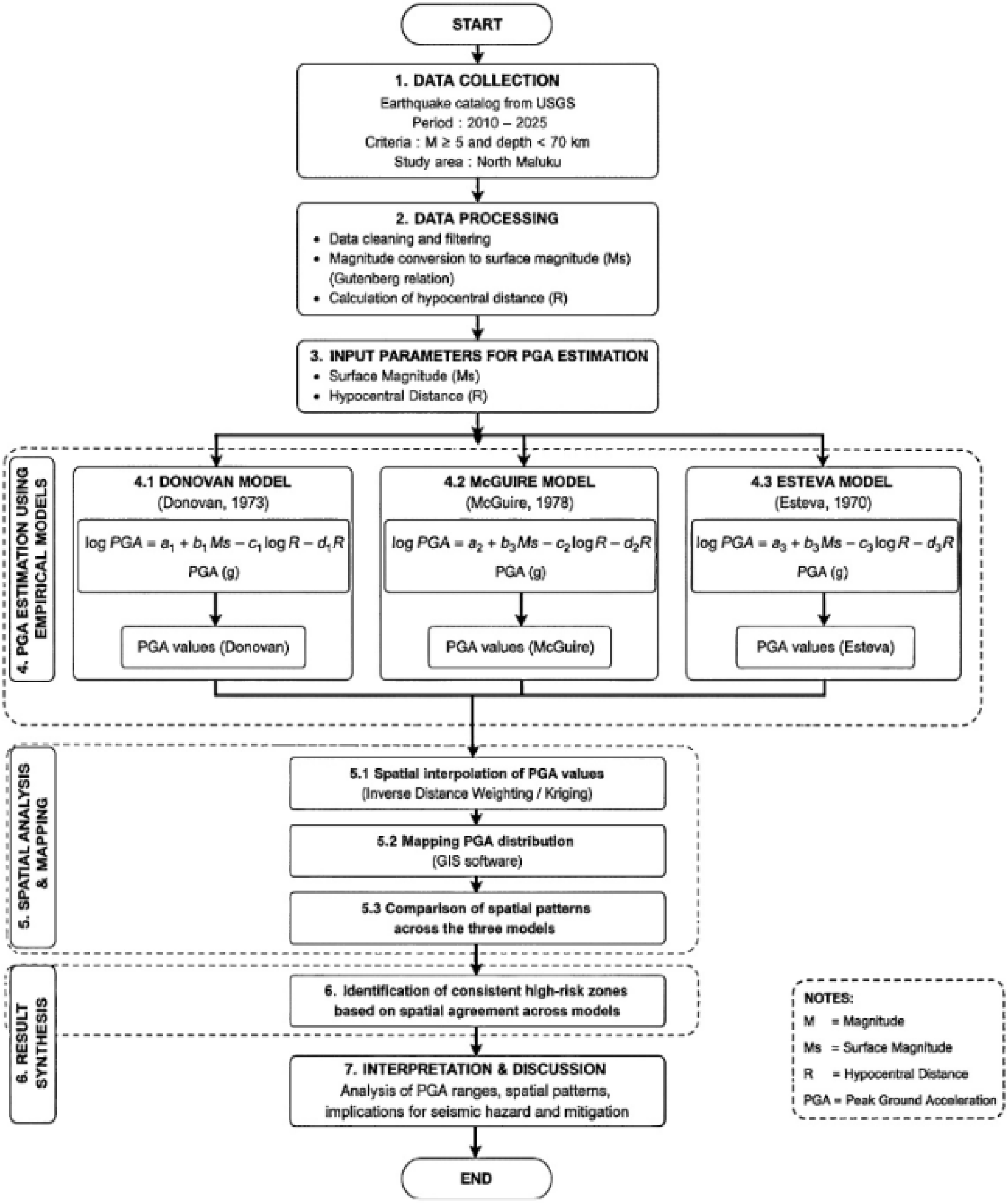

Figure 2. Flowchart of the research methodology, from data processing and PGA estimation to spatial analysis and seismic hazard zonation in North Maluku.

Earthquake data, including event time, epicenter location, magnitude, and depth, are first collected and processed to ensure accuracy and consistency. This initial stage is crucial for selecting representative events and preparing the dataset for further analysis. Once the raw parameters are validated, the next step is to calculate the surface magnitude (Ms), which serves as the primary input for estimating peak ground acceleration (PGA).

The calculation of Ms follows the Gutenberg formula, which adjusts the instrumental magnitude for depth and regional attenuation effects. This approach ensures that the magnitude reflects the actual shaking potential at Earth's surface, rather than just the seismic energy released at the hypocenter. The formula for obtaining the Ms value is:

$$Mb = 0.56Ms + 2.9$$
$$Mb = 1.7 + 0.8ML - 0.01ML^2 \quad (1)$$

Based on these calculations, the relationship between M_L and Mb is obtained to determine the Ms value as follows:

$$Ms = \frac{0.8ML - 0.01ML^2 - 1.2}{0.56}$$

$$Ms = \frac{Mb - 2.9}{0.56} \quad (2)$$

After obtaining the Ms value, PGA calculations were performed using three empirical approaches with the following formulation, which has also been used in research [11] Donovan(α_D), McGuire(α_M), and Esteva(α_E) [12]

$$\alpha_D = \frac{1080 * Exp(0.5Ms)}{(R+25)^{1.32}} \quad (3)$$

$$\alpha_M = \frac{472.3 * 10^{0.278Ms}}{(R+25)^{1.301}} \quad (4)$$

$$\alpha_E = \frac{5600 * Exp(0.5Ms)}{(R+40)^2} \quad (5)$$

where R is the hypo-center in km, and Ms is the Surface Magnitude.

The values determined from each model are mapped. The result is a Peak Ground Acceleration map. PGA values were mapped for the entire region; however, in this research, only the land area is depicted. A comparative analysis of the Donovan, McGuire, and Esteva models was conducted to evaluate differences in attenuation behavior, probabilistic characteristics, and depth sensitivity. Validation was conducted by comparing the spatial distribution patterns and PGA ranges generated by the three empirical models. Although numerical PGA values varied among the methods, consistent identification of high-risk zones along the eastern and northern coasts of Halmahera indicates strong spatial agreement and methodological reliability. In addition, the resulting hazard patterns were qualitatively compared with previous regional tectonic and seismicity studies in North Maluku. This comparison ensured that the estimated PGA distributions remained consistent with known tectonic structures, subduction systems, and historical seismic activity in the region. The spatial convergence observed across multiple empirical models provides indirect validation of the robustness and reliability of the seismic hazard zonation results.

The discussion used a comparative-interpretative approach to analyze differences in PGA magnitude across the Donovan, McGuire, and Esteva models. The analysis also examined the spatial consistency of seismic hazard zones and the influence of tectonic conditions and attenuation characteristics on the distribution of PGA. In addition, the results were interpreted in terms of their implications for seismic hazard mitigation and infrastructure planning.

Results and Discussion

The North Maluku region lies within a highly complex and dynamic tectonic system formed by the collision of the Eurasian and Pacific Plates, and the Halmahera and Sangihe microplates. This interaction, which leads to double subduction, is the primary cause of the region's significant seismic activity. Tomographic investigations using BMKG data and traveltime data verified the presence of a twin subduction zone in the Molucca Sea-Halmahera, with a slab trajectory increasing from north to south. [13]

Several significant earthquakes, including a magnitude 7.2 event, were detected during the observation period, suggesting the potential for substantial shaking along the Molucca-Halmahera subduction zone.[14] The epicenter distribution pattern is crucial for determining Peak Ground Acceleration (PGA) values using the Donovan, McGuire, and Esteva approach in the early phases of the study. The dominant distribution of earthquake locations on the eastern side of Halmahera is consistent with earlier research on the subsurface tectonic structure in this region[15], implying that the epicenter distribution map serves as a spatial basis for additional seismic investigations.[15]

The PGA is the most important statistic in the evaluation of seismic buildings, as it represents the maximum perceived ground motion at a given location due to earthquakes. In this study, the PGA distribution was modeled using three different empirical methods: Donovan, McGuire, and Esteva. The third method uses seismic data from the Maluku Islands to obtain quantitative estimates of land fire intensity. The results of each approach are visualized as PGA points and are discussed further in the following sections.

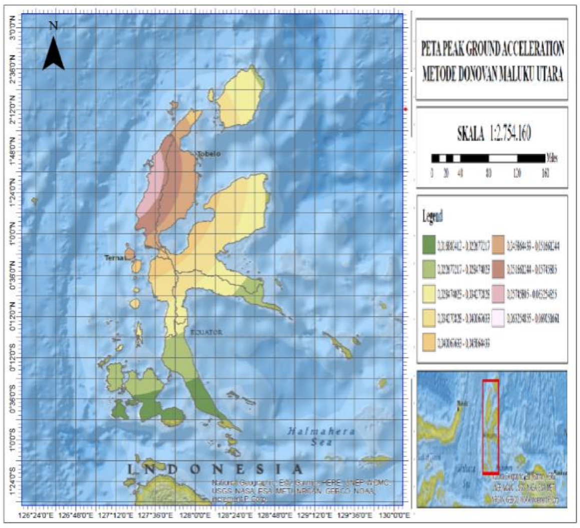

Figure 3. Spatial distribution of Peak Ground Acceleration (PGA) in North Maluku derived using the Donovan model.

Peak Ground Acceleration (PGA) values on the map range from 0.0168g to 0.0690g, with the east and north coasts of Halmahera having the largest concentrations. The possibility of significant shaking from shallow earthquakes is indicated by the red-orange zones. PGA values ranged from 23 to 33 gal (~0.023 to 0.033g) using the Donovan formula, indicating that the acceleration levels in North Maluku are fairly high in the local context.[13] The Donovan method, which has an exponential formula between magnitude and distance, is consistent with the approach used in the Risk Mitigation study in Malang.

A greater PGA of 0.0225g to 0.0905g is estimated by the McGuire approach, which covers a larger risk zone that includes the central coast and nearby islands. In accordance with McGuire's conservative consistency pattern in comparison to Donovan, research conducted in Malang likewise reveals PGA levels using the McGuire approach ranging from 22–31 gal (~0.022–0.032g).[8] In a rather congested location, McGuire's function in seismic structural security is supported by the highest range on the North Maluku map.

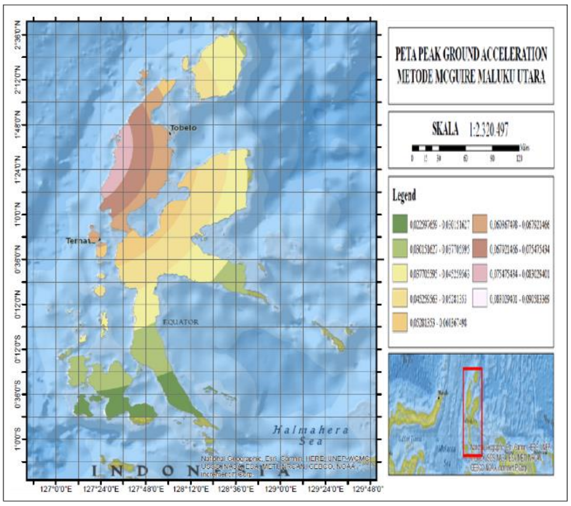

Figure 4. Spatial distribution of Peak Ground Acceleration (PGA) in North Maluku derived using the McGuirre model.”

Esteva's estimate provides a lower PGA (0.0014g-0.0107g), but its spatial distribution pattern is comparable to that of the other two techniques. This method includes hypocenter depth in the formula, making it appropriate for regional analysis, such as the Sulawesi study, which demonstrated the local accuracy of mono-parametric GMPE.[16] Despite the low PGA values, Halmahera's northern and eastern coasts remain a top focus for mitigating efforts.

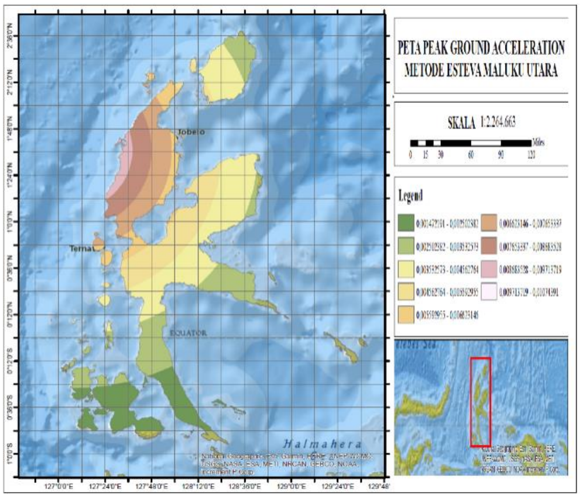

Figure 5. Spatial distribution of Peak Ground Acceleration (PGA) in North Maluku derived using the Esteva model.

All three approaches indicate spatial consistency in the distribution of high-potential zones across the coasts of northern and eastern Halmahera, but their values differ. McGuire's technique has the highest and most conservative PGA, making it excellent for structural design. Donovan's is quite reliable and easy to use, while Esteva's is more moderate, making it useful for seismic depth investigation. These findings are congruent with the implications of regional GMPE for West Java, which shows that integrating local variability, such as earthquake type and geological conditions, improves PGA forecast accuracy[17].

The observed discrepancies among Donovan, McGuire, and Esteva highlight the methodological diversity in PGA estimation, reflecting differences in attenuation modeling, probabilistic conservatism, and depth sensitivity. Employing a multi-method framework strengthens the robustness of seismic hazard analysis by integrating complementary perspectives. This comprehensive approach provides a scientifically rigorous foundation for regional development planning, disaster mitigation strategies, and infrastructure resilience. In seismically active regions such as Northern Maluku, adopting such pluralistic methodologies ensures that policy and engineering decisions are informed by reliable, context-specific insights, thereby reducing vulnerability and enhancing long-term societal stability.

The discrepancies observed in the range of PGA values across the three empirical approaches - Donovan, McGuire, and Esteva - highlight the inherent methodological distinctions embedded within each model. Donovan’s formulation, while relatively simple, has demonstrated consistent success in capturing the general attenuation of seismic waves with distance. McGuire’s approach, on the other hand, tends to be more conservative, reflecting its probabilistic orientation and emphasis on hazard quantification under uncertainty. Esteva’s model introduces an additional layer of refinement by explicitly accounting for hypo-central depth, thereby offering a more nuanced representation of local geological and tectonic conditions.

The application of these three methods in parallel provides a multidimensional perspective on seismic hazard estimation. Rather than relying on a single empirical relationship, integrating multiple approaches allows researchers to triangulate results, identify systematic biases, and better capture the variability inherent in earthquake ground motion. This methodological pluralism enhances the robustness of hazard assessments, ensuring that the derived PGA values are not only statistically reliable but also contextually relevant to the seismic environment of Northern Maluku.

The findings of this study provide important scientific and practical contributions to the field of seismic hazard analysis, particularly in tectonically active regions with limited instrumental seismic records. The comparative evaluation of the Donovan, McGuire, and Esteva empirical models demonstrates that although each model produces different numerical PGA estimates, all consistently identify similar high-risk spatial zones in North Maluku.

This finding suggests that spatial agreement across multiple Ground Motion Prediction Equations (GMPEs) may be a more reliable indicator of seismic hazard than reliance on a single empirical model. Consequently, the study contributes to advancing multi-model seismic hazard assessment frameworks by emphasizing spatial consistency as a key parameter in hazard reliability evaluation.

Scientifically, this research contributes to the development of comparative GMPE-based seismic hazard methodologies. It also supports refining regional seismic zonation approaches by providing a more comprehensive evaluation of seismic hazard characteristics. In addition, this study promotes the integration of spatial consistency analysis into empirical PGA assessment.

Practically, the resulting PGA distribution maps can support earthquake-resistant infrastructure planning. The findings are also useful for the development of disaster mitigation policies and regional spatial planning. In addition, this study contributes to seismic risk reduction strategies in North Maluku and other tectonically active regions.

Several limitations should be acknowledged in this study. First, the analysis relies exclusively on empirical Ground Motion Prediction Equations (GMPEs), which may not fully capture local geological complexity and site-specific amplification effects. Second, the study uses earthquake catalog data from the USGS database without incorporating local strong-motion accelerograph records due to limited data availability in North Maluku. Third, the spatial analysis focuses primarily on magnitude, hypocenter distance, and depth parameters, while other important variables, such as local soil conditions, fault mechanisms, basin effects, and surface geology, were not explicitly incorporated into the PGA modeling process.

In addition, the comparison among the three empirical models remains qualitative-comparative rather than fully probabilistic. Therefore, the resulting PGA values should be interpreted as regional seismic-hazard indicators rather than precise site-specific ground-motion predictions.

Future studies are recommended to incorporate local geological and geotechnical parameters, including soil amplification and site classification: integrate additional Ground Motion Prediction Equations (GMPEs) and probabilistic seismic hazard analysis (PSHA) approaches, utilize local accelerograph and BMKG seismic datasets for calibration and validation purposes, apply machine learning and hybrid modeling approaches to improve PGA prediction accuracy, conduct micro zonation studies at city or district scales for more detailed seismic risk assessment.

Integrating empirical modeling through advanced numerical simulations and GIS-based multi-hazard analysis is highly recommended. This integration will improve the reliability and applicability of seismic hazard assessments in North Maluku and other tectonically active regions.

A comprehensive analysis of seismic hazard provides a critical foundation for regional development planning. Accurate PGA estimation can inform the design of earthquake-resistant infrastructure, support the formulation of disaster mitigation policies, and strengthen community resilience against seismic risk. Tectonically active regions, such as North Maluku, experience significant seismic hazards due to their complex geological settings. A multi-method framework ensures that planning and policy decisions are based on a scientifically rigorous understanding of seismic behavior, thereby reducing vulnerability and supporting long-term socio-economic stability.

Conclusion

The results demonstrate that the McGuire method produced the highest Peak Ground Acceleration (PGA) estimates in North Maluku, ranging from 0.0225g to 0.0905g, followed by the Donovan method (0.0168g–0.0690g) and the Esteva method (0.0014g–0.0107g). Despite differences in numerical values, all three empirical models consistently identified high-seismic-hazard zones along the eastern and northern coasts of Halmahera, indicating strong spatial agreement in ground-motion distribution. This study confirms that spatial consistency across multiple Ground Motion Prediction Equations (GMPEs) provides a more reliable framework for seismic hazard zonation than reliance on a single empirical model. The integration of multiple empirical approaches, therefore, enhances the robustness and reliability of regional seismic hazard assessments in tectonically active areas such as North Maluku.

Scientifically, this study advances comparative GMPE-based seismic hazard methodologies by emphasizing spatial convergence as a key indicator of hazard reliability. Practically, the resulting PGA zonation maps provide valuable information for earthquake-resistant infrastructure design, disaster mitigation strategies, spatial planning, and seismic risk reduction in North Maluku. Nevertheless, this study is limited by the exclusive use of empirical models and the absence of local strong-motion and site-specific geological data. Therefore, future research should integrate local geotechnical conditions, probabilistic seismic hazard analysis (PSHA), local accelerograph datasets, and advanced modeling approaches such as machine learning and GIS-based multi-hazard analysis to improve the accuracy and applicability of seismic hazard assessment.

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