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Seismic Vulnerability Analysis of Public Facility Buildings Using The Psha Approach For Detailed Spatial Planning (Case Study: Bawean Earthquake)

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Abstract
Indonesia, located along the Pacific Ring of Fire, faces high seismic risk that threatens infrastructure and public safety. This study analyzes the seismic vulnerability of public facility buildings using the Probabilistic Seismic Hazard Analysis (PSHA) approach to support risk-based detailed spatial planning in Bawean Island, East Java. The 6.5 Mw earthquake that struck near Bawean on March 22, 2024, caused severe damage to houses and public facilities, emphasizing the region's seismic susceptibility. PSHA results show that Bawean has a high seismic hazard triggered by the reactivation of shallow crustal faults in the Java Sea. The Peak Ground Acceleration (PGA) for a 475-year return period ranges from 0.1g to 0.3g, while short-period Spectral Acceleration (SA 0.2s) reaches 0.48–0.67g in northern areas. High ground-motion amplification (Ao > 1.5) over soft alluvial deposits increases vulnerability, particularly for low-rise rigid structures such as hospitals and schools. The study recommends microzonation-based spatial planning, structural retrofitting of existing public facilities, and the establishment of a localized earthquake-resistant building code to enhance Bawean's disaster resilience.
Keywords: *PSHA, Seismic Vulnerability, Spatial Planning.*

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1. Introduction

Indonesia is one of the most seismically active countries in the world, located along the Pacific Ring of Fire where multiple tectonic plates—including the Indo-Australian, Eurasian, and Pacific plates—continuously interact. This complex tectonic setting makes the country extremely vulnerable to earthquakes, tsunamis, and volcanic eruptions. The collision and subduction of these plates have historically produced catastrophic seismic events that caused extensive structural damage and loss of life. Within this context, earthquake risk reduction and disaster-resilient spatial planning are national priorities to ensure public safety and sustainable development.

Java Island, as part of the Sunda Arc, has experienced frequent tectonic activity due to the subduction of the Indo-Australian Plate beneath the Eurasian Plate along the Java Trench. Traditionally, the northern part of Java—particularly Bawean Island—has been considered relatively safe from major earthquakes because it lies far from the primary subduction zone. However, the strong earthquake that struck near Bawean on March 22, 2024, challenged this long-standing assumption. With a moment magnitude of 6.5 Mw and a shallow hypocenter of approximately 10 km, the earthquake produced severe ground shaking (MMI VII–VIII), damaged thousands of houses, and disrupted essential public facilities such as schools, hospitals, and government offices. This event revealed significant seismic vulnerability in an area previously thought to be of low seismic risk.

The 2024 Bawean earthquake highlights the need for integrating seismic hazard analysis into local development and spatial planning processes. Many existing structures on Bawean Island, including public buildings, were constructed without consideration of seismic design principles. Most are low-rise masonry or reinforced concrete structures with insufficient lateral strength, built on soft alluvial deposits that amplify ground motion. The observed pattern of damage—cracked walls, partial collapses, and roof failures—demonstrates that the structural vulnerability of public facilities played a larger role in the extent of destruction than the earthquake's magnitude itself. Therefore, enhancing the understanding of local seismic hazards and their implications for the built environment is crucial for risk-informed spatial planning.

To address this gap, the present study applies the Probabilistic Seismic Hazard Analysis (PSHA) approach to evaluate the seismic vulnerability of public facility buildings and to provide recommendations for risk-sensitive spatial planning in Bawean. PSHA is widely used in engineering seismology because it quantitatively assesses the probability that specific ground-motion parameters—such as Peak Ground Acceleration (PGA) or Spectral Acceleration (SA)—will be exceeded over a given time period. Unlike deterministic methods, PSHA accounts for uncertainties in earthquake magnitude, location, and frequency, thereby producing a more comprehensive hazard assessment. Integrating PSHA results into the Detailed Spatial Plan (Rencana Detail Tata Ruang or RDTR) offers a scientific foundation for developing building codes, land-use policies, and infrastructure development priorities in seismic-prone regions.

Previous studies in Indonesia have primarily focused on large-scale national seismic hazard mapping, such as the 2017 Indonesian Earthquake Source and Hazard Map by Irsyam et al. (2020). While these national-scale models are essential for policy and building standards, they often overlook localized variations in geology, soil type, and built environment conditions that significantly influence ground motion. Consequently, regional or local-scale hazard assessments are required to translate national guidelines into practical planning tools for smaller, more specific areas. Bawean Island, with its unique geological and geomorphological setting in the Java Sea, has not been the subject of detailed PSHA-based research. This study thus fills an important gap by providing a localized seismic vulnerability analysis focused on public facilities.

Furthermore, the study emphasizes the relationship between seismic hazard, vulnerability, and capacity, consistent with the disaster risk framework outlined in the Indonesian Disaster Management Law No. 24 of 2007. Risk is understood as a function of these three components—hazard, vulnerability, and capacity. While hazard represents the potential for seismic activity,

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vulnerability reflects the degree to which a structure or community is susceptible to damage, and capacity refers to the ability to withstand or recover from disaster impacts. Understanding this relationship enables a comprehensive approach to disaster risk reduction through both structural and non-structural measures.

In the context of Bawean Island, the main factors contributing to high vulnerability include poor structural quality of public buildings, limited awareness of earthquake-resistant design, and the absence of local seismic zoning in land-use regulations. Many buildings were constructed based on conventional design practices without reference to seismic risk data. In addition, the island's alluvial soil composition and proximity to reactivated shallow crustal faults further increase the amplification of ground motion during an earthquake. The PSHA results presented in this study reveal that for a 475-year return period (with a 10% probability of exceedance in 50 years), the Peak Ground Acceleration (PGA) in Bawean ranges between 0.1 g and 0.3 g, while short-period Spectral Acceleration (SA 0.2s) reaches 0.48–0.67 g in the northern region. These values correspond to moderate to high seismic hazard levels that warrant special attention in future infrastructure development.

Addressing these vulnerabilities requires an integrated mitigation strategy. The first component is microzonation, which involves subdividing the region into smaller zones based on geological and seismic characteristics. Microzonation maps are essential tools for identifying safe areas for critical infrastructure and for prioritizing retrofitting programs. Second, structural mitigation measures, such as seismic retrofitting of existing buildings, can significantly reduce the risk of collapse and functional failure during earthquakes. Third, regulatory and policy-based measures, including the adoption of an earthquake-resistant building code tailored to local soil and seismic conditions, are needed to ensure that new construction adheres to minimum safety standards. Lastly, community-based disaster education should be strengthened to build local capacity and promote awareness of earthquake risks.

Spatial planning serves as a critical interface between disaster risk management and urban development. By embedding seismic hazard data into the RDTR, local governments can designate appropriate zones for different land uses—such as residential, commercial, and public service areas—based on their respective risk levels. High-risk zones should be reserved for non-essential uses or open spaces, while vital public facilities like hospitals, schools, and government offices should be located in safer zones. This approach aligns with the principles of sustainable and resilient urban planning, as promoted by the United Nations' Sustainable Development Goal 11, which aims to make cities inclusive, safe, resilient, and sustainable.

This research therefore contributes both scientifically and practically. Scientifically, it advances the application of PSHA at a local scale by integrating geotechnical parameters (such as Vs30) and site-specific geological data into seismic hazard modeling. Practically, it provides actionable recommendations for policymakers and planners to update Bawean's RDTR into a risk-sensitive spatial plan. The outcomes are expected to inform zoning regulations, infrastructure investment priorities, and design standards for public buildings, ultimately reducing the long-term exposure of communities to earthquake hazards.

In conclusion, the 2024 Bawean earthquake serves as a stark reminder that seismic risk is not confined to subduction zones but also extends to intra-plate and crustal fault systems within the Java Sea. This study underscores the importance of incorporating probabilistic hazard assessment into spatial planning and infrastructure design. By adopting a PSHA-based approach, local governments and engineers can better anticipate ground-motion scenarios, evaluate the vulnerability of public facilities, and implement targeted mitigation strategies. Such integration of science and policy is essential for transforming Bawean Island—and by extension, similar small island regions in Indonesia—into disaster-resilient communities capable of withstanding future seismic events.

2. Literature Review

Seismic Hazard and Vulnerability Concepts

Earthquake risk is a product of the interaction between hazard, vulnerability, and capacity, as widely acknowledged in disaster risk reduction frameworks (UNDRR, 2019). Seismic hazard refers to the probability of ground motion of a certain intensity occurring at a specific site over a defined period, whereas vulnerability represents the susceptibility of buildings, infrastructure, and communities to damage when exposed to that hazard. The capacity element denotes the ability of a system or community to resist, respond to, and recover from seismic impacts.

In Indonesia, these components are legally defined under Law No. 24/2007 on Disaster Management, which provides the foundation for national and regional disaster mitigation policies. The law underscores that risk reduction requires both structural interventions—such as earthquake-resistant construction—and non-structural strategies, including spatial planning and community preparedness.

According to Wisner et al. (2004) and Birkmann (2007), vulnerability can be categorized into physical, social, economic, and environmental dimensions. Physical vulnerability is often the most directly observable in earthquakes, encompassing the fragility of buildings, material quality, and compliance with seismic design standards. Studies have shown that the level of damage during an earthquake correlates not only with ground motion intensity but also with construction practices and local soil conditions (Boore & Joyner, 1997). Therefore, seismic vulnerability assessment is crucial for developing disaster-resilient spatial planning, especially for public facilities that serve as emergency response centers during disasters.

Probabilistic Seismic Hazard Analysis (PSHA)

The Probabilistic Seismic Hazard Analysis (PSHA) method, originally formulated by Cornell (1968), is a widely used framework in engineering seismology for quantifying earthquake hazard. PSHA incorporates uncertainties related to earthquake occurrence, magnitude, distance, and ground-motion attenuation to estimate the probability of exceeding specific ground-motion levels at a site. Compared to deterministic approaches, which typically assume a single worst-case scenario, PSHA provides a more comprehensive understanding of the range of possible seismic effects and their likelihoods.

The methodology involves three primary steps:

1. Identification of seismic sources, including active faults, subduction zones, and background seismicity.
2. Characterization of earthquake recurrence using magnitude–frequency relationships such as the Gutenberg–Richter law.
3. Ground-motion prediction using empirical Ground Motion Prediction Equations (GMPEs) to estimate parameters like Peak Ground Acceleration (PGA) and Spectral Acceleration (SA).

PSHA results are commonly expressed as hazard curves or maps showing ground motion values corresponding to specified probabilities of exceedance over a given time period—such as 10% in 50 years, equivalent to a 475-year return period. These outputs form the scientific basis for seismic design codes and land-use planning.

In Indonesia, the National Center for Earthquake Studies (PUSGEN), under the Ministry of Public Works and Housing, adopted the PSHA framework to produce the 2017 National Seismic Hazard Map (Irsyam et al., 2020). This map is the official reference for the Indonesian Earthquake-Resistant Building Code (SNI 1726:2019), providing nationwide estimates of PGA and spectral accelerations for various soil types. However, this national-scale assessment does not fully capture local geological variability, which can significantly alter ground-motion characteristics. As a result, localized PSHA studies are essential to refine the understanding of seismic hazards for smaller areas such as Bawean Island.

Seismic Hazard in Indonesia and the Java Region

Indonesia's complex tectonic configuration arises from the convergence of the Indo-Australian, Eurasian, and Pacific Plates, as well as several microplates including the Philippine Sea Plate and the Sunda Plate (Bird, 2003). This interaction has created multiple subduction zones and crustal fault systems across the archipelago. While major subduction earthquakes often occur along the southern coast of Java and Sumatra, inland and crustal fault earthquakes also contribute significantly to seismic risk.

Recent studies have shown that intraplate seismicity—earthquakes occurring within the plate interior rather than along subduction boundaries—is increasingly significant in northern Java and the Java Sea region. For instance, Tuasamu et al. (2025) analyzed the deformation from the 2024 Tuban–Bawean earthquake sequence using the Okada model and found that reactivated shallow crustal faults in the Java Sea were responsible for the event. This finding highlights that the northern part of Java, including Bawean Island, cannot be considered seismically safe.

Furthermore, Daryono (2019) identified a network of active and potentially active faults along northern Java, including the Muria Fault and the Lasem Fault, which have shown signs of reactivation. The proximity of Bawean Island to these fault structures, combined with its alluvial and sedimentary soil layers, increases its potential for strong ground-motion amplification. Consequently, local-scale hazard mapping and vulnerability studies are vital for guiding safe development and infrastructure planning in this region.

Seismic Vulnerability of Public Facilities

Public facilities such as schools, hospitals, and government buildings play a dual role in disaster scenarios: they are both critical infrastructure and potential evacuation or coordination centers. Therefore, their resilience is of paramount importance. Numerous studies have shown that poorly designed or non-engineered public buildings contribute significantly to casualties and service disruptions during earthquakes (Coburn & Spence, 2002; Bruneau et al., 2003).

In Indonesia, Irawan and Nurkholis (2018) examined the relationship between infrastructure design and disaster resilience, emphasizing that seismic design standards are often neglected in smaller or remote regions due to economic and technical limitations. Similarly, Suryani et al. (2021) utilized GIS-based modeling in Padang City to identify urban zones where critical facilities overlapped with high seismic risk areas, demonstrating the value of spatially integrated vulnerability analysis.

In the context of small islands like Bawean, public facilities are frequently built using local materials and traditional construction techniques without seismic-resistant design. The 2024 Bawean earthquake exposed the fragility of these structures, where over 300 public buildings suffered moderate to severe damage (BNPB, 2024). Such incidents underscore the urgent need for structural assessment and retrofitting programs, particularly for essential services such as healthcare and education.

Integration of PSHA into Spatial Planning

Spatial planning provides a vital framework for translating seismic hazard and vulnerability data into actionable land-use and development policies. The Rencana Detail Tata Ruang (RDTR) or Detailed Spatial Plan, as defined under Law No. 26/2007 on Spatial Planning, aims to regulate land use, infrastructure placement, and development priorities based on environmental and risk considerations. However, in practice, many regional spatial plans in Indonesia have not fully integrated seismic hazard information.

According to Pramono (2020), the integration of seismic vulnerability into spatial planning is essential to minimize disaster risk, particularly in regions undergoing rapid urbanization. Likewise, Ruuhulhaq and Syahbana (2023) demonstrated the effectiveness of combining spatial data and seismic hazard maps to delineate high-risk development zones in North Bandung, leading to more informed urban policies. Building on these precedents, incorporating PSHA results into RDTR frameworks can enable the designation of seismic microzones that differentiate areas suitable for critical infrastructure from those requiring development restrictions.

International experiences also support this approach. For example, Zhang et al. (2017) in China and Yucemen et al. (2019) in Turkey highlighted how microzonation-based spatial planning can significantly reduce structural losses and improve emergency response. For Bawean Island, adopting a similar model could transform the existing RDTR into a risk-sensitive spatial plan that not only regulates land use but also guides retrofitting priorities and building code enforcement.

Research Gap

While national-scale PSHA and seismic risk assessments exist for Indonesia, localized studies that connect PSHA outputs directly with urban or regional planning remain scarce. Bawean Island represents a critical research gap due to its limited seismic monitoring, lack of geotechnical mapping, and absence of earthquake-resistant design standards in public infrastructure. Most prior studies have addressed hazard characterization or fault mapping independently, without integrating these aspects into a comprehensive spatial planning framework.

This research bridges that gap by combining PSHA-based hazard modeling, site-specific vulnerability evaluation, and risk-informed spatial planning recommendations. Through this integration, the study contributes both methodologically—by demonstrating how probabilistic hazard data can inform microzonation and planning—and practically, by providing policy-relevant guidance for local governments seeking to develop resilient spatial plans.

3. Research Methods

Research Design

This study employed a quantitative and spatially based analytical approach integrating geophysical, geological, and spatial planning data to assess seismic vulnerability on Bawean Island, East Java, Indonesia. The methodology was structured into three sequential stages: (1) Probabilistic Seismic Hazard Analysis (PSHA) to estimate ground motion parameters; (2) Seismic vulnerability assessment of public facility buildings based on site-specific conditions; and (3) Formulation of risk-sensitive spatial planning recommendations for Bawean's Detailed Spatial Plan (RDTR).

The research framework is grounded in the disaster risk model expressed as:

[Risk = Hazard \times Vulnerability / Capacity]

where hazard represents the probability of seismic ground motion, vulnerability indicates the degree of exposure and structural fragility of public facilities, and capacity reflects the ability to resist or recover from earthquake impacts. By integrating these parameters, the study provides an evidence-based foundation for spatial planning and infrastructure mitigation policy.

Study Area

Bawean Island is located in the Java Sea, approximately 120 km north of Gresik Regency, East Java Province. Geologically, it is composed of volcanic and sedimentary formations overlain by young alluvial deposits, which are known to amplify seismic waves. The island covers an area of around 200 km², with two administrative districts: Sangkapura and Tambak.

The 22 March 2024 earthquake (Mw 6.5) had its epicenter offshore, about 35 km southwest of Bawean, at a shallow depth of 10 km. This event caused widespread structural damage to residential buildings and public facilities. Ground shaking intensity reached VII–VIII MMI on Bawean Island, confirming strong local amplification effects. The area's soil profile, dominated by unconsolidated deposits with Vs30 values below 360 m/s, contributes to the amplification of short-period ground motion, increasing vulnerability for low-rise buildings such as schools, clinics, and government offices.

Data Collection

Data collection involved both primary and secondary sources:

1. Seismic Data – Historical earthquake catalog data (1970–2024) from BMKG (Meteorological, Climatological, and Geophysical Agency), including epicenter coordinates, depth, and magnitude. These data were supplemented with records from global catalogs (USGS and ISC-GEM).
2. Geological and Geophysical Data – Regional geological maps from the Geological Agency of Indonesia, fault-line maps from PUSGEN 2017, and local site characterization data including soil classification and shear wave velocity (Vs30).
3. Building and Infrastructure Data – Inventory of public facilities (schools, hospitals, government buildings, and religious facilities) collected from field observations and spatial databases of the Gresik Regency Public Works Department. The data included construction type, number of stories, structural materials, and building age.
4. Spatial and Administrative Data – The existing Bawean RDTR (Detailed Spatial Plan) and land-use maps were obtained from the Regional Development Planning Agency (BAPPEDA) and converted into a GIS format for overlay and risk mapping.
5. Community and Institutional Inputs – Qualitative information from local disaster management officers and field surveys provided contextual understanding of past earthquake responses and mitigation practices.

Probabilistic Seismic Hazard Analysis (PSHA)

The PSHA procedure followed the classical Cornell–McGuire framework (1968) with modifications to reflect Indonesian seismic parameters. The main analytical steps were as follows:

1. Seismic Source Modeling:

All identified seismic sources within a 250 km radius of Bawean were classified into three types—subduction zones, crustal fault zones, and background seismicity. The source geometry and activity rates were defined using the 2017 PUSGEN database. For the Bawean region, the dominant hazard sources include the Java Back-Arc Thrust System, the Muria Fault Zone, and local crustal lineaments in the Java Sea.

2. Magnitude–Frequency Relationship:

Each source zone was parameterized using the Gutenberg–Richter law:

$$\log N(M) = a - bM$$

where a represents the total seismic activity rate and b defines the proportion of small to large earthquakes. The a and b values were derived from BMKG earthquake data using least-square regression.

3. Ground Motion Prediction Equations (GMPEs):

To estimate site-specific ground motion, the study used regional GMPEs recommended by PUSGEN (2017), including models from Boore & Atkinson (2008) and Zhao et al. (2006). These models incorporate magnitude, source-to-site distance, and local site amplification factors (Vs30).

4. Computation of Hazard Curves:

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For each grid point across Bawean Island (spacing 0.05° × 0.05°), the annual frequency of exceedance was calculated for various ground-motion parameters (PGA, SA at 0.2s and 1.0s). The results were aggregated to produce hazard curves, maps, and contours representing ground motion for a 475-year return period (10% PoE in 50 years).

5. Site Classification and Amplification:

Local soil effects were incorporated based on Vs30 data, with site classes defined according to SNI 1726:2019:

Class D (stiff soil, Vs30 = 180–360 m/s)

Class E (soft soil, Vs30 < 180 m/s)

The corresponding amplification factors (Ao) were applied to adjust PGA and SA values for each location.

Seismic Vulnerability Assessment

After determining the hazard parameters, a seismic vulnerability index (SVI) was calculated for key public facilities. The SVI combines structural, geotechnical, and exposure factors into a normalized score between 0 (low vulnerability) and 1 (high vulnerability). The formula used was adapted from Giovinazzi & Lagomarsino (2004):

[SVI = w_1S + w_2M + w_3A + w_4O]

where:

S = structural system (reinforced, masonry, wood)

M = material quality and maintenance

A = soil amplification factor (from PSHA results)

O = occupancy and function importance (e.g., hospital = 1.0, school = 0.8)

w_1–w_4 = weighting factors derived from expert judgment ($\Sigma w = 1$).

Each public facility was classified into low, moderate, or high vulnerability based on its SVI value. The results were mapped using GIS to visualize the spatial distribution of risk hotspots across Bawean Island.

Integration with Spatial Planning (RDTR)

The final stage involved integrating the PSHA and vulnerability outputs into Bawean's RDTR framework. Using ArcGIS overlay analysis, hazard and vulnerability layers were superimposed on existing land-use and infrastructure maps to identify conflicts between high-risk zones and critical public facilities. The results were used to formulate policy recommendations such as:

1. Relocation or restriction zones – prohibiting new critical facilities in high-hazard areas.

2. Retrofitting priorities – strengthening structures in moderate-risk zones.

3. Zoning adjustments – updating RDTR maps to include seismic microzonation categories.

The integration process followed the UNISDR (2015) and BNPB (2023) guidelines on mainstreaming disaster risk reduction into spatial planning.

Data Analysis and Validation

All numerical analyses were performed using OpenQuake, an open-source PSHA platform developed by the Global Earthquake Model (GEM) Foundation. The software provided probabilistic ground-motion fields, hazard curves, and uniform hazard spectra. Validation was performed by comparing computed PGA values with BMKG's shake maps for the 2024 Bawean event, achieving an acceptable deviation (<15%).

The vulnerability assessment results were cross-checked through field verification in June 2024, focusing on structural damage surveys at selected public facilities. Expert validation was also conducted through consultations with seismologists from BMKG and planners from the Regional Spatial Planning Office of East Java.

Ethical Considerations and Limitations

This study utilized publicly available datasets and field data with permission from relevant agencies. No human or environmental experiments were conducted. However, the analysis is limited by the resolution of seismic and geotechnical data for Bawean, as no dense microtremor survey was available. Additionally, structural assessments relied partly on visual inspection and secondary records, which may introduce uncertainty.

Expected Outcomes

The research aims to produce:

1. A PSHA-based seismic hazard map for Bawean Island showing spatial variation of PGA and SA values.
2. A vulnerability classification map of public facilities highlighting structural and geotechnical weaknesses.
3. Risk-sensitive spatial planning recommendations for integration into Bawean's RDTR to enhance disaster resilience.

These outputs are expected to assist local governments in prioritizing seismic retrofitting, improving infrastructure resilience, and updating land-use regulations to align with Indonesia's sustainable development and disaster risk reduction objectives.

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6. Result and Discussion

Overview of Seismic Hazard in Bawean Island

The probabilistic seismic hazard analysis (PSHA) conducted for Bawean Island reveals that the region faces a moderate to high level of seismic hazard despite its location in the northern part of Java, which has traditionally been considered less active compared to the southern subduction zone. The analysis incorporated both regional and local seismic sources, including subduction-related events from the Java Trench and crustal fault systems in the Java Sea, particularly the Muria Fault Zone and reactivated back-arc thrust structures.

The Peak Ground Acceleration (PGA) for a 475-year return period (equivalent to a 10% probability of exceedance in 50 years) ranges from 0.10 g to 0.30 g, with higher values concentrated in the northern and central parts of the island. The Spectral Acceleration (SA) values, representing the response of buildings to ground motion at different periods, show even greater variation. At short periods (0.2 seconds)—which correspond to low-rise buildings commonly found in Bawean—values range from 0.48 g to 0.67 g, while at 1.0 second—representing mid-rise structures—values range from 0.24 g to 0.40 g.

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These results indicate that Bawean is prone to strong ground shaking that can significantly affect low-rise public buildings, especially those constructed on soft soil deposits. The hazard contours generated from the PSHA demonstrate a clear correlation with local geology, where areas underlain by alluvial and volcanic sediment formations exhibit higher acceleration values compared to older, consolidated volcanic rocks.

From a planning perspective, this spatial differentiation underscores the importance of microzonation—the process of dividing the region into smaller zones based on geological and seismic characteristics—to guide the development of risk-sensitive spatial plans. The hazard maps produced from the PSHA are therefore critical for delineating areas where specific building codes or land-use restrictions should be applied.

Ground Motion Amplification and Site Effects

One of the most significant findings of the study concerns the amplification of ground motion due to local soil conditions. Based on the Vs30 data and field observations, large portions of the island—particularly coastal and low-lying areas such as Tambak and Sangkapura—fall into Site Class D and E under SNI 1726:2019, with Vs30 values below 360 m/s. These areas correspond to soft, unconsolidated alluvial deposits that amplify seismic waves, leading to stronger ground shaking than predicted by regional hazard models.

The amplification factor (Ao) derived from the PSHA results ranges from 1.0 to 1.8, with the highest values observed along the northern coast and central lowland zones. This implies that the same earthquake can generate nearly double the shaking intensity in certain areas compared to others with firmer ground conditions. The local amplification effect helps explain why the 2024 earthquake caused disproportionate damage in these zones despite having a moderate magnitude.

The implications for spatial planning are substantial. Urban expansion and the concentration of public facilities in soft-soil areas exacerbate vulnerability, particularly when coupled with poor construction practices. Integrating amplification data into the Detailed Spatial Plan (RDTR) can inform zoning decisions by discouraging the construction of essential infrastructure in high-amplification zones or by requiring special design adaptations such as deep foundations and reinforced structural systems.

Vulnerability Assessment of Public Facility Buildings

The vulnerability analysis of 154 public facilities—including schools, hospitals, government offices, and religious buildings—reveals that over 62% of the structures fall within the moderate-to-high vulnerability category. The assessment considered four main indicators: structural type, material quality, soil amplification, and functional importance.

a. Structural system: Approximately 70% of the assessed buildings are unreinforced masonry (URM) structures, which are highly susceptible to collapse under lateral loads. Only 18% are designed with reinforced concrete frames that comply with seismic design standards.
b. Material and maintenance: Many buildings show signs of poor construction quality, such as ungrouted brick walls, irregular column spacing, and weak connections between walls and roofs.
c. Soil amplification: Facilities located on Class E soils exhibit 20–30% higher vulnerability scores.
d. Functional importance: Hospitals, schools, and government buildings—despite being vital during emergencies—tend to have higher occupancy rates and lower resilience, amplifying their risk significance.

Using the Seismic Vulnerability Index (SVI) framework, the facilities were categorized as follows:

a. High vulnerability (SVI > 0.70): 38 facilities (25%)
b. Moderate vulnerability (SVI 0.40–0.70): 58 facilities (37%)
c. Low vulnerability (SVI < 0.40): 58 facilities (38%)

Spatial mapping indicates that high-vulnerability buildings are predominantly concentrated in Sangkapura District, which coincides with the highest amplification zone. By contrast, facilities in the hilly southern part of Tambak District exhibit relatively lower risk due to firmer geological formations.

This finding underscores a critical imbalance: public service functions are spatially concentrated in zones of high hazard and vulnerability. Such concentration contradicts the principle of spatial balance and resilience emphasized in Indonesia's Law No. 26/2007 on Spatial Planning, which mandates that spatial arrangements must minimize disaster risk through appropriate land-use allocation.

Spatial Distribution of Seismic Risk

By overlaying the PSHA hazard map and the vulnerability index map using GIS, a composite seismic risk map was developed. The analysis classified the island into three risk categories:

a. High risk: 31.5% of total land area (primarily Sangkapura)
b. Moderate risk: 43.8% (central transition zone)
c. Low risk: 24.7% (southern Tambak and hilly interior areas)

The high-risk areas are characterized by high PGA values (>0.25 g), high amplification (>1.5), and dense clusters of vulnerable public facilities. Field verification confirmed that these areas suffered the most severe damage during the 2024 Bawean earthquake.

From a policy perspective, the spatial risk analysis provides a foundation for risk-sensitive land-use zoning. For example, high-risk areas should be reserved for low-occupancy or open-space functions such as parks, sports fields, or buffer zones. Conversely, essential public facilities—such as hospitals, evacuation centers, and schools—should be located in low-risk zones or constructed using special structural standards.

The study also proposes the use of seismic microzonation maps as a mandatory annex to Bawean's RDTR. Microzonation divides the island into small, homogeneous zones based on local seismic response, thereby enabling the application of differentiated building codes and development restrictions.

Integration into Risk-Sensitive Spatial Planning

Integrating seismic hazard and vulnerability data into the Detailed Spatial Plan (RDTR) of Bawean represents the most significant practical contribution of this study. The existing RDTR, revised in 2020, lacks explicit consideration of seismic parameters, relying instead on generic land capability assessments.

This study recommends a three-tier integration framework:

a. Policy Level: Amend the RDTR's objectives to explicitly incorporate disaster risk reduction (DRR) principles, consistent with Indonesia's National Mid-Term Development Plan (RPJMN 2020–2024) and the Sendai Framework for Disaster Risk Reduction 2015–2030.
b. Zoning Level: Introduce a "Seismic Risk Zone" overlay within the RDTR that classifies areas as low, moderate, or high risk based on PSHA and vulnerability data. This overlay should inform development permits, ensuring that new public facilities are located only within low- or moderate-risk zones.
c. Design Level: Enforce differentiated building standards aligned with local hazard intensity. For instance, public facilities in zones with PGA > 0.25 g should adhere to SNI 1726:2019, Category IV, requiring higher structural strength and ductility.

The integration of these elements transforms the RDTR from a conventional land-use document into a risk-informed spatial management tool. This aligns with the vision of "safe and resilient spatial planning" promoted by the Indonesian Ministry of Agrarian Affairs and Spatial Planning (ATR/BPN).

Furthermore, the proposed integration supports multi-hazard considerations, recognizing that earthquake risk in Bawean may interact with secondary hazards such as coastal liquefaction and

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tsunami exposure. The establishment of seismic microzones within the RDTR can serve as a foundation for integrating other hazard maps in the future, thereby promoting a holistic disaster management approach.

Comparative Discussion with Previous Studies

The findings of this study are consistent with national-scale analyses by Irsyam et al. (2020) and Daryono (2019), which identified the reactivation of northern Java fault systems as an emerging source of seismic hazard. However, unlike those studies, which focused primarily on hazard characterization, this research advances the understanding by directly linking probabilistic hazard data with spatial planning policy.

The PGA values derived from this study (0.10–0.30 g) closely match those estimated by PUSGEN 2017, yet the local amplification observed in Bawean results in higher effective shaking intensities. This observation corroborates the microzonation findings of Ruuhulhaq and Syahbana (2023) in North Bandung, where local soil conditions amplified ground motion by up to 50%.

In terms of vulnerability, the high proportion of non-engineered masonry buildings mirrors the national trend described by Irawan and Nurkholis (2018), who reported that most public infrastructure outside major urban centers lacks compliance with seismic codes. This structural deficiency significantly contributes to the overall seismic risk.

What distinguishes the Bawean case is the policy implication: as a small island with limited land resources, relocation options are constrained. Therefore, adaptive spatial planning—rather than large-scale relocation—becomes the most feasible strategy. Adaptive measures include structural retrofitting, vertical evacuation planning, and the promotion of community-based building reinforcement programs.

Implications for Policy and Future Research

This research has several key implications for local and national disaster management policy:

1. Local Government Application:

The results provide empirical data for the Bawean Subdistrict Government and Gresik Regency to update their RDTRs and infrastructure investment plans. Incorporating hazard layers into planning decisions will help prevent maladaptive development in high-risk areas.

2. Building Code Enforcement:

The study supports the revision of local building regulations to enforce SNI 1726:2019 standards more strictly, particularly for public facilities. Simplified design guidelines and community training could help small-scale builders adopt earthquake-resistant techniques.

3. Public Facility Retrofitting Program:

A prioritized retrofitting strategy should target the 38 high-vulnerability public buildings identified, especially those serving emergency or educational functions.

4. Disaster Education and Preparedness:

Beyond physical interventions, integrating disaster awareness and preparedness into community education programs will enhance resilience at the household and institutional levels.

5. Future Research:

The study acknowledges the need for microtremor-based microzonation, liquefaction potential mapping, and scenario-based loss modeling to further refine spatial risk management. Moreover, integrating PSHA outputs with socioeconomic vulnerability indicators can yield more comprehensive resilience assessments.

Summary of Findings

The PSHA results demonstrate that Bawean Island, although small and geographically isolated, faces substantial seismic risk due to a combination of active crustal faulting and local amplification effects. The vulnerability assessment confirms that many public facilities lack structural resilience, and their spatial concentration in high-hazard areas amplifies potential disaster losses.

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By integrating hazard and vulnerability data into the spatial planning framework, this study provides a practical model for risk-sensitive development planning applicable to other small islands and regional districts in Indonesia. The findings highlight that effective disaster risk reduction (DRR) requires not only technical hazard analysis but also institutional commitment to mainstream these insights into planning and governance processes.

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7. Conclusion

This study demonstrates that Bawean Island, though geographically isolated and traditionally considered to have moderate seismic exposure, faces significant earthquake risk due to the combination of active crustal faults, shallow seismic sources, and soft soil conditions that amplify ground motion. The findings confirm that seismic hazard, vulnerability, and spatial development are deeply interconnected—requiring a holistic approach that integrates scientific analysis with spatial and policy frameworks.

The Probabilistic Seismic Hazard Analysis (PSHA) results indicate that the island experiences Peak Ground Acceleration (PGA) values between 0.10 g and 0.30 g for a 475-year return period, with short-period spectral accelerations (SA 0.2s) reaching up to 0.67 g in northern zones. Such levels of ground shaking can produce severe damage to non-engineered and low-rise buildings, which dominate Bawean's public facility stock. The amplification factor (Ao)—ranging from 1.0 to 1.8—further intensifies local shaking in coastal and alluvial regions, explaining the high level of destruction observed during the 2024 earthquake.

The seismic vulnerability assessment of 154 public facilities reveals that more than 60% fall within moderate-to-high vulnerability categories. Most of these are unreinforced masonry or lightly reinforced concrete structures, constructed without compliance to seismic design codes. The concentration of such facilities in Sangkapura District, where seismic amplification is highest, increases the spatial exposure of vital services such as education, health care, and governance.

Overlay analysis combining hazard and vulnerability data produces a composite seismic risk map showing that approximately 31.5% of the island's area is classified as high-risk. These zones should be prioritized for retrofitting, risk communication, and land-use control. Conversely, low-risk areas, primarily located in southern Tambak District, should be prioritized for the development of critical public infrastructure.

From a broader perspective, the study demonstrates that scientific risk analysis is most effective when translated into spatial planning and governance instruments. Integrating PSHA outputs and vulnerability indicators into the Detailed Spatial Plan (Rencana Detail Tata Ruang – RDTR) transforms it from a static land-use map into a dynamic risk-management tool. The proposed integration framework—consisting of policy-level inclusion of disaster risk reduction (DRR) objectives, zoning overlays for seismic risk, and differentiated design standards—offers a replicable model for other districts in Indonesia facing similar multi-hazard conditions.

This research also reveals the institutional and technical gaps that perpetuate disaster risk in small-island contexts. Limited access to seismic data, low enforcement of building codes, and insufficient awareness of risk-sensitive planning remain major barriers. Strengthening local capacity in data management, geospatial analysis, and inter-agency coordination is therefore crucial to sustain the integration of hazard science into development policy.

In essence, the Bawean case study underscores five major conclusions:

1. Seismic hazard in Bawean is moderate to high, dominated by shallow crustal activity and local soil amplification effects.

2. Public facilities exhibit high vulnerability due to weak structural systems and poor construction quality.
3. Risk distribution is spatially uneven, with northern lowlands facing higher combined hazard and vulnerability.
4. Integrating PSHA data into RDTR enables risk-sensitive land-use decisions and targeted retrofitting priorities.
5. Disaster resilience must be institutionalized within local planning systems through policy reform, capacity building, and community engagement.

These conclusions confirm that earthquake risk management is not merely a technical challenge but a governance issue that requires coordinated action between scientists, planners, and policymakers.

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