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A Participatory GIS Framework for Multi-Hazard Climate Risk Mapping in Indonesia

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Abstract. Climate change has emerged as a global crisis with severe consequences for tropical and coastal regions. Pekalongan Regency, Indonesia, exemplifies these challenges, facing recurrent floods and landslides that threaten livelihoods and infrastructure. Risk mapping is urgently needed to guide adaptation strategies, yet many regions face constraints due to limited data availability. This study develops a multi-hazard risk mapping approach that integrates Geographic Information System (GIS) technology with stakeholder participation through Public Participation GIS (PPGIS). Hazard and vulnerability analyses were conducted using disaster records, socio-economic indicators, and spatial datasets, validated through Focus Group Discussions (FGDs) with government agencies and local stakeholders. The findings were synthesized into a structured four-stage framework encompassing stakeholder education (Kick-off), preliminary spatial analysis, participatory indicator validation, and finalization of risk maps. Results reveal distinct spatial patterns: flood risks dominate northern coastal and riverine villages, while landslide hazards are concentrated in the southern highlands. Stakeholder involvement not only improved data validity but also enhanced local adaptive capacity. The proposed PPGIS framework provides a transferable model for participatory climate resilience planning, particularly in data-scarce regions such as the global south area.

Keywords: public participation GIS, multi-hazard risk mapping, spatial vulnerability assessment, climate risk assessment, disaster risk reduction

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1. Introduction

Climate change has emerged as an undeniable global crisis, profoundly affecting ecosystems, human health, and socio-economic stability, with tropical and coastal nations bearing the brunt of its impacts. Countries such as Indonesia, the Philippines, and Bangladesh are among the most exposed, facing intensified extreme events including heatwaves, floods, and droughts, often referred to as manifestations of global boiling [1–3] Coastal zones are particularly vulnerable, where rising sea levels threaten livelihoods, infrastructure, and land resources. In Indonesia, climate projections up to 2045 indicate an increase in daily rainfall by 2.5 mm/day and temperature rise of 0.45–0.74°C [4]. By the end of the century, rainfall is expected to intensify during the wet season while declining in the dry season [5]. These changes critically affect four key sectors, namely agriculture, health, water, and fisheries. Farming patterns are disrupted by shifting seasons and extreme weather, heightening crop failures [6]. Health burdens increase due to vector- and water-borne diseases such as dengue, malaria, and diarrhea [7]. Meanwhile, water resources oscillate between recurrent flooding and prolonged droughts, with economic losses projected to reach USD 7.25 billion in Indonesia by 2024 [4,8]. These risks underscore the urgency of climate-resilient development integrated into national planning, as reflected in the RPJMN 2025–2029 and the National Action Plan for Greenhouse Gas Reduction (RAN-GRK), aligned with the Paris Agreement's temperature goals.

Pekalongan Regency in Central Java epitomizes the compound threats of climate change. This coastal district experiences recurrent flooding and tidal inundation, driven by high rainfall, sea-level rise, tidal surges, and land subsidence [9,10]. Sea-level rise in Pekalongan is 5 mm/year, which is higher than the Java Sea average of 3.9 mm/year [11], and and is exacerbated by severe land subsidence [9]. Alongside floods and tidal floods, the region is also affected by droughts, landslides, and tornadoes [12,13]. Given these multi-hazard conditions, disaster risk mapping becomes indispensable for precise spatial targeting and policy formulation [14,15]. Previous studies have demonstrated the utility of GIS-based spatial analysis for hazard mapping, employing overlay and multi-criteria weighted techniques [16–18]. However, these approaches are constrained by their reliance on secondary socio-economic data, which is often scarce or incomplete in Indonesia, particularly at village scales [19–21]. This limitation raises a critical question: How can disaster risk mapping be made more representative, context-sensitive, and reliable in data-limited environments such as Indonesia's coastal regions?

To address this challenge, this study introduces a Participatory GIS (PPGIS) framework that integrates conventional GIS analysis with community engagement. While PPGIS has been widely applied in spatial planning [22–24], its application in multi-hazard climate risk mapping at regional scales remains underexplored. Strong validation mechanisms involving governments, communities, academics, and data providers are embedded, as participatory and collaborative approaches have been shown to yield risk maps that are both more accurate and locally relevant [25]. Additionally, this framework leverages integrated data sources such as remote sensing, tabular data, and stakeholder participation to increase the trustworthiness of the outputs [26,27]. Accordingly, the objectives of this paper are twofold: first, to map climate change, induced disaster risks in Indonesia by integrating GIS technology with public participation; second, to develop a generalized framework based on this empirical experience, outlining the process of integrating GIS with participatory inputs to produce representative risk maps. Beyond its national relevance, this framework is designed to be transferable and adaptable to other countries facing similar challenges such as the global south area, thereby advancing the global discourse on participatory climate resilience planning.

2. **Methods**

2.1. Study location and data

The research was conducted in Pekalongan Regency, Central Java, Indonesia (Figure 1). The regency features diverse morphology, ranging from fluvial plains to denudational hills with altitudes between 0 and 2,177 m. Approximately 24.76% of the territory (22,224.66 ha) consists of denudational hills (500–1,000 m) prone to landslides, while low-lying fluvial plains are highly susceptible to flooding. Settlement patterns reflect this topography: Buaran District (river plain) records the highest population density (6,690/km²), while Petungkriyono District (mountainous terrain) records the lowest (183/km²). This distribution illustrates how geomorphological factors influence natural vulnerability [28].

Figure 1. Study area

2.2. Data and climate change disaster risk analysis in Pekalongan Regency

The climate change disaster risk map in this study is in the village administrative unit. This study only focuses on two climate change disasters, namely floods and landslides. This is because they are the disasters that most often hit Pekalongan Regency[29]. The data needed in this study is data on natural disaster events in the period 2021, 2022 and 2023 from the Pekalongan Regency Regional Disaster Management Agency (BPBD). The next main data is village potential statistical data (PODES), and several spatial data such as land cover, ecoregion and others. The methodology for assessing climate change disaster risk in Pekalongan Regency is formulated as a function of Hazard and Vulnerability, which are defined as follows:

- Hazard refers to the impacts of climate change, determined by the characteristics, magnitude, rate of change, and variability of climate [30,31], This is different from other disaster concepts such as susceptibility which only shows the location of potential disasters or the impact of climate change without magnitude or frequency.
- Vulnerability is the susceptibility of a system to climate change, influenced by Exposure, Sensitivity, and Adaptive Capacity [32].

2.2.1. Climate Hazard Index Calculation

The hazard index is calculated by analyzing climate-related disaster data, including disaster events and threat maps provided by BPBD. The hazard level (H) is classified into five levels: Very High (VH), High (H), Moderate (M), Low (L), and Very Low (VL). Areas with no recorded disaster events or those outside disaster-prone zones are classified as safe or no hazard.

2.2.2. Vulnerability Analysis

Vulnerability to climate change is determined by three dimensions: Exposure, Sensitivity, and Adaptive Capacity [33,34]. Vulnerability is assessed using a spatial vulnerability assessment approach based on Exposure–Sensitivity Indicators (ESI) and Adaptive Capacity Indicators (ACI), derived from bio-physical, environmental, and socio-economic data. These indicators are weighted and normalized, with vulnerability classified into five levels: Very Low, Low, Moderate, High, and Very High. Each vulnerability builder indicator is obtained from literature studies, then agreed upon through Focus Group

Discussion (FGD) (Table 1). FGD involves several government agencies in Pekalongan Regency, this not only helps answer the indicator representation, but also answers the availability of data.

Table 1. Vulnerability indicators

Exposure-Sensitivity Indicators (ESI)	Data Collection Source	Data Analysis Technique
Village topography	DEM SRTM data	Zonal statistics - Topography classification - scoring
Poverty rate	PODES data, Central Bureau of Statistics Pekalongan Regency	Scoring
Main livelihood sources		
Fuel sources		
Toilet facilities		
Waste disposal sites		
Clean water access		
Population density	PODES data, Central Bureau of Statistics Pekalongan Regency	Population density calculation - scoring
Dependency ratio	PODES data, Central Bureau of Statistics Pekalongan Regency	Dependency ratio calculation - scoring
Vulnerable population	PODES data, Central Bureau of Statistics Pekalongan Regency	Scoring
Malnutrition cases		
Water carrying capacity class	Water Carrying Capacity Map, Pekalongan Regency Environment Agency	Scoring
Agricultural area	Land use map, Pekalongan Regency Environment Agency	Scoring
Food insecurity	FSVA map, Pekalongan Regency Food Security Agency	Scoring
Built-up land	Land use map, Pekalongan Regency Environment Agency	Scoring
Geomorphology	Ecoregion Map, Pekalongan Regency Environment Agency	Scoring
Land subsidence	Land subsidence monitoring data, Central Java Energy and Mineral Resources Agency	Interpolation analysis - scoring
Slope gradient	DEM SRTM data	Slope analysis - classification - scoring
Coastal areas	PODES data, Central Bureau of Statistics Pekalongan Regency	Scoring
Adaptive Capacity Indicators (ACI)	**Data Collection Source**	**Data Analysis Technique**
Educational facilities	PODES data, Central Bureau of Statistics Pekalongan Regency	Scoring
Health facilities		
Road infrastructure		
Institutions		
Communication		
Small and micro industries	Industry and Trade Agency, Pekalongan Regency	Scoring
Economic infrastructure	PODES data, Central Bureau of Statistics Pekalongan Regency	Scoring

Credit facilities received		
Financial institutions		
Social activities		
Environmental conservation		
Community empowerment programs		
Number of community groups		
Distance to Local Activity Center	Spatial planning map, Pekalongan Regency	Buffer analysis - classification - scoring
Distance to main road		
Drainage density	Public Works Agency, Pekalongan Regency	Drainage density calculation (drainage length/area) - scoring
Disaster control infrastructure		Scoring
Hydrogeology	Hydrology map, Pekalongan Regency Environment Agency	Scoring
Vegetated canopy area (Ha)	Land use map, Pekalongan Regency Environment Agency	Scoring
Irrigation areas	Public Works Agency, Pekalongan Regency	Scoring
Number of water service customers	Public Works Agency & PDAM, Pekalongan Regency	Scoring
Number of health insurance holders	PODES data, Central Bureau of Statistics Pekalongan Regency	Scoring
Number of textile (batik) & craft SMEs	Industry and Trade Agency, Pekalongan Regency	Scoring

Source: analysis results

2.2.3. Risk Analysis

Risk (R) was quantified as a function of hazard and vulnerability:

$$\mathbf{R = f (H , V)}$$

A risk matrix was applied to classify areas into five levels (Very Low–Very High) [35]. Spatial analysis and overlay operations were performed in ArcMap 10.8, enabling visualization and integration of hazard and vulnerability layers. Descriptive analysis complemented the spatial results to interpret drivers of risk.

2.3 Public Participation GIS and its framework development

To integrate local knowledge into risk mapping, this study employed Public Participation GIS (PPGIS) by involving key stakeholders such as BAPPEDA, the Environmental Agency, BPBD, the Public Works Department, and the Food Security Agency. These actors jointly determined vulnerability indicators and their weights through Focus Group Discussions (FGDs). This participatory mechanism not only ensured the contextual accuracy of selected indicators but also addressed critical data gaps by introducing proxy measures aligned with local realities [36]. The PPGIS process was designed as an iterative cycle that combined the collection of official statistics, spatial datasets, and local knowledge with intensive stakeholder engagement for indicator selection and weighting. The outcomes were further validated through cross-checking with both expert assessments and community input, ensuring reliability and acceptance. Finally, the empirical practices and participatory results were synthesized into a structured framework that integrates GIS-based analysis with stakeholder contributions. This phased yet cohesive approach allowed the development of a generalizable framework for multi-hazard risk mapping, grounded in collaborative decision-making and iterative validation, which not only serves as a methodological guide for Pekalongan but also offers transferability to other regions facing similar climate-related challenges [37].

3. Results and Discussion

3.1. Hazard Analysis

Hazard analysis was conducted by identifying disaster events, consequence data, and threat indices. Disaster event and consequence data were obtained from BPBD for 2021–2023, while threat indices were derived from BPBD's Disaster Threat Map. Hazard indices for each type of hazard in every district were categorized into five levels, ranging from very low to very high (Figure 2).

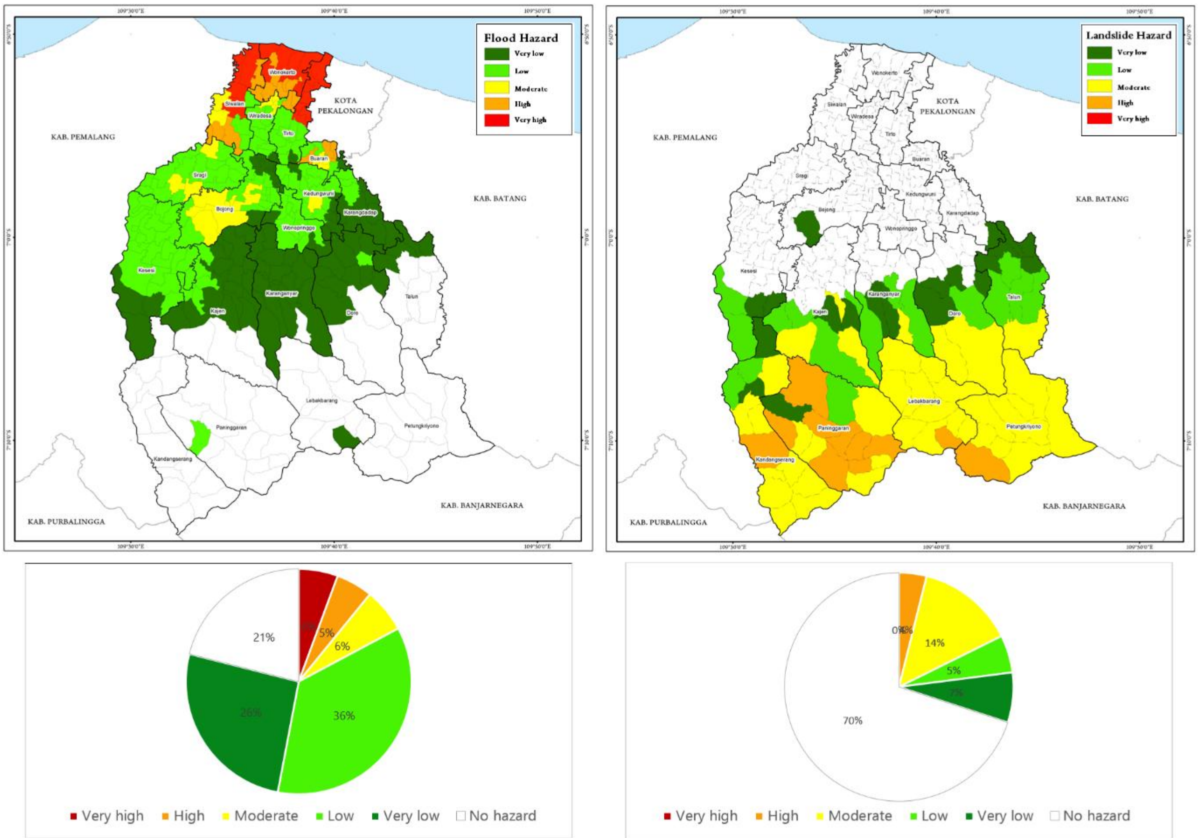

Figure 2. Flood and landslide hazard map

Flood hazards in Pekalongan Regency encompass both tidal flooding and river overflows, affecting 225 villages located primarily in riverine and coastal areas. Approximately 36% (102 villages) are classified as low risk, while villages in Tirto, Wonokerto, and Siwalan Districts are classified as very high hazard due to their fluvial morphology and coastal proximity, rendering them highly prone to tidal inundation. Land subsidence in these districts further amplifies flood risk [10]. Villages located near the coast and affected by river overflow, particularly in Tirto District, also experience significant flooding [38].

Landslide hazards are concentrated in 73 villages located on steep slopes and hilly areas. About 73% (198 villages) are categorized as safe, while 14% (39 villages) are at moderate hazard levels. The highest hazard areas are concentrated in Paninggaran, Lebakbarang, Petungkriyono, and Kandangserang Districts. The southern region of Pekalongan Regency, characterized by steep slopes and volcanic, denudational, and structural landforms, is particularly vulnerable. Paninggaran and Kandangserang, which form part of the Karangkobar hill range in Banjarnegara Regency, demonstrate a notably high susceptibility to landslides [29].

3.2. Vulnerability Analysis

Vulnerability analysis began with the identification of Vulnerability Indicators, consisting of Exposure–Sensitivity Indicators (ESI) and Adaptive Capacity Indicators (ACI). These indicators were developed through stakeholder discussions and informed by biophysical, environmental, and socio-economic data from PODES (Village Potential Statistics) compiled by BPS and related agencies. The indicators reflected the three dimensions of vulnerability namely, exposure, sensitivity, and adaptive capacity, allowing local governments to track changes over time and adapt programs accordingly. Literature studies and FGDs (Focus Group Discussions) were used to refine both indicator selection and weighting.

Within the ESI, the coastal area indicator carried the highest weight (0.18), followed by land subsidence (0.15) and poverty levels (0.08) (Figure 3). The prominence of coastal exposure is explained by the prevalence of tidal flooding, which has already rendered much agricultural land unproductive, even during the dry season [39]. Land subsidence contributes to tidal flooding, accelerates seawater intrusion, and damages infrastructure and homes [40]. Poverty exacerbates disaster impacts by limiting community access to healthcare, education, and infrastructure [41,42].

Exposure-Sensitivity Indicators (ESI) - Total Weight = 1.00

Weight	Indicator
0.07	Poverty rate
0.04	Main livelihood sources
0.02	Village topography
0.02	Fuel sources
0.01	Toilet facilities
0.02	Waste disposal sites
0.05	Clean water
0.06	Population density
0.04	Dependency ratio
0.06	Vulnerable population
0.04	Malnutrition cases
0.04	Water carrying capacity class
0.05	Agricultural area
0.04	Food insecurity
0.04	Built-up land
0.04	Geomorphology
0.15	Land subsidence
0.03	Slope gradient
0.18	Coastal areas

Adaptive Capacity Indicators (ACI) - Total Weight = 1.00

Weight	Indicator
0.08	Educational facilities
0.08	Health facilities
0.01	Road infrastructure
0.04	Institutions
0.02	Communication
0.03	Small and micro industries
0.06	Economic infrastructure
0.03	Credit facilities received by community
0.06	Financial institutions
0.03	Social activities
0.03	Environmental conservation activities
0.07	Community empowerment programs (environment & disaster)
0.05	Number of community groups
0.05	Distance to Local Activity Center
0.02	Distance to main road
0.01	Drainage density
0.05	Disaster control infrastructure
0.08	Hydrogeology
0.03	Vegetated canopy area (Ha)
0.03	Irrigation areas
0.05	Number of PDAM/Pamsimas customers
0.06	Number of health insurance holders
0.03	Number of textile (batik) & craft SMEs

Figure 3. ESI and ACI indicators and weights from literature studies and FGDs

For the ACI, education and healthcare facilities received the highest weight (0.8). Access to education improves adaptive capacity [43,44], while schools and universities double as evacuation hubs. Healthcare facilities provide essential emergency medical care and preparedness programs [45,46]. Community empowerment initiatives, with a weight of 0.07, were also significant, reflecting programs such as DESTANA (Disaster-Resilient Villages), which promote awareness, local resource mobilization, and early warning systems. These initiatives enhance collective resilience to climate hazards.

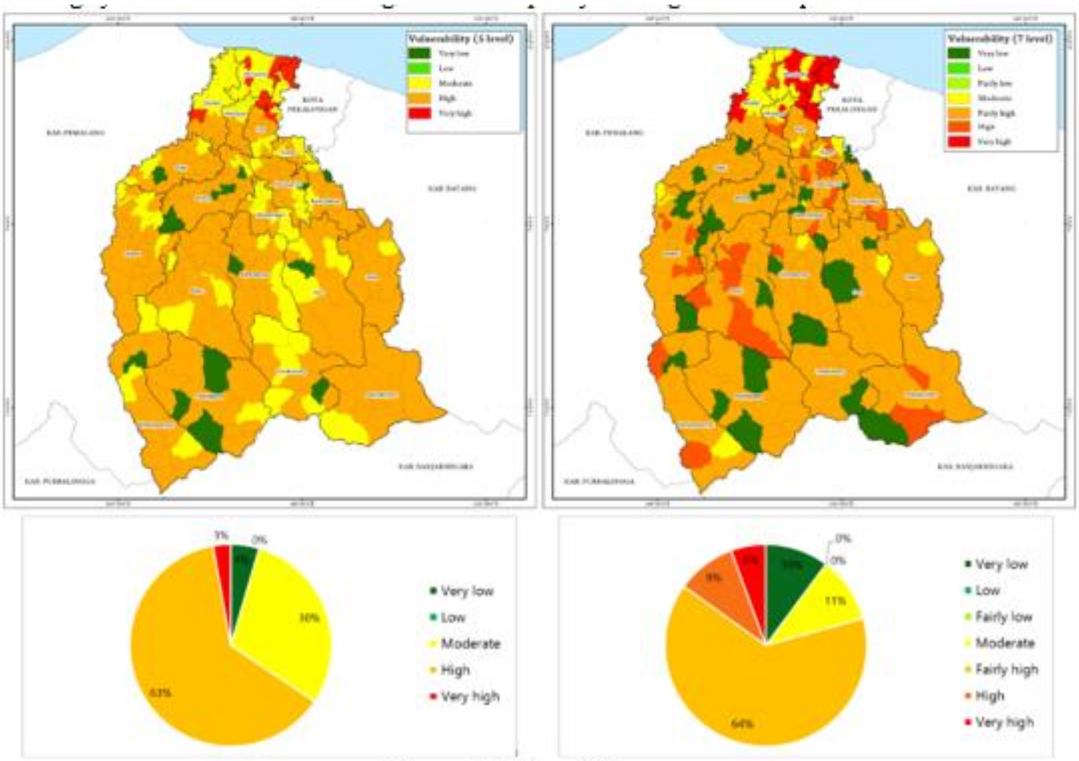

Figure 4. Vulnerability map

Weighting was then applied to normalize indicator values, generating vulnerability levels. Although most results were moderate, stakeholders recommended reconstructing the classification into seven levels for better granularity: Very Low (VL), Low (L), Fairly Low (FL), Moderate (M), Fairly High (FH), High (H), and Very High (VH) (Figure 4). The results show that 183 villages fall into the "fairly high" category, 27 into "high," and 16 into "very high." These findings underscore widespread vulnerability in Pekalongan, particularly in coastal areas affected by land subsidence. Some coastal villages nevertheless showed "moderate" vulnerability due to factors such as a strong SME sector, robust disaster control infrastructure, and high levels of community participation, all of which enhanced adaptive capacity. The analysis highlights both the scale of vulnerability and the importance of strengthening adaptation programs such as ProKlim and Destana, which remain limited in coverage.

3.3. Risk Analysis

The integration of hazard and vulnerability assessments produced the risk maps (Figure 5). Flood risk in Pekalongan Regency is predominantly low (34%), affecting 96 villages. However, villages in Tirto, Wiradesa, and Wonokerto Districts were classified as very high risk due to the convergence of high hazard and high vulnerability. Coastal villages with very high hazards but moderate vulnerability were categorized as high risk, reflecting the mitigating role of adaptive capacity.

Landslide risk was primarily moderate (12%), affecting 35 villages. High-risk zones such as Depok Village (Lebakbarang District) and Simego Village (Petungkriyono District) were characterized by steep slopes, high hazard levels, and moderate vulnerability. These areas require targeted interventions such as slope stabilization, early warning systems, and community preparedness programs to mitigate the impacts of future landslides.

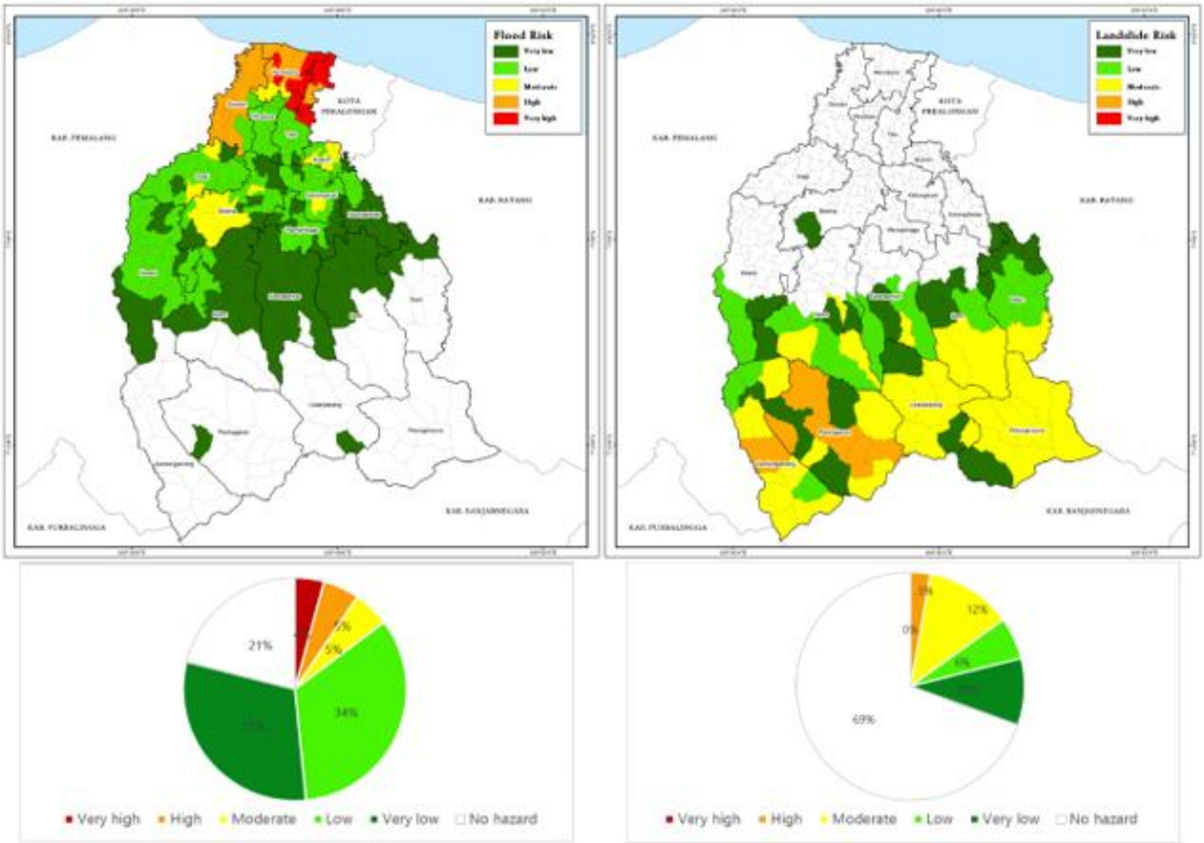

Figure 5. Flood and landslide risk map

3.4. Framework PPGIS for Multi-Hazard Climate Change Risk Mapping

Stakeholder input through FGDs was crucial for adjusting risk levels, demonstrating that historical disaster records and conventional spatial analysis cannot fully capture regional realities. This is particularly relevant given the rapid advances in GIS-based risk modeling using machine learning and deep learning techniques [47,48]. While these approaches have strong technical capabilities, they lack the contextual accuracy that arises from community validation. Integrating GIS with stakeholder knowledge significantly enhances both the credibility of risk maps and their utility for disaster management [49].

The results of our PPGIS approach demonstrate that the risk maps produced were more representative, as stakeholders functioned not only as data providers but also as validators. This distinguishes our approach from Patel & Patel [50], which relied solely on climatological, environmental, and spatial indices within a traditional GIS framework, and from Gohil et al. [51], which combined GIS with fuzzy logic for multi-hazard mapping but depended entirely on expert judgment without community participation. By contrast, the validation role of stakeholders in our framework ensured that both the indicators and the resulting maps were locally grounded, socially legitimate, and policy-relevant.

Our framework (Figure 6) comprises several stages: stakeholder education (Kick-off), preliminary spatial analysis, FGDs for indicator validation and adjustment, and the finalization of maps. This phased approach is adaptable across different regions and ensures that stakeholders not only understand the underlying concepts of vulnerability, hazard, exposure, and sensitivity [52,53] but also play an active role in validating outcomes.Compared to the multi-stage structure proposed by Fagerholm et al. [54], our framework maintains the Explore and Explain phases but adds a recurring participatory cycle that emphasizes validation. Whereas approximately 80% of vulnerability assessments rely solely on secondary data [19,55], our approach systematically integrates ground-truthing and stakeholder validation. This methodological triangulation not only strengthens data validity but also enhances adaptive capacity at the community and institutional levels.

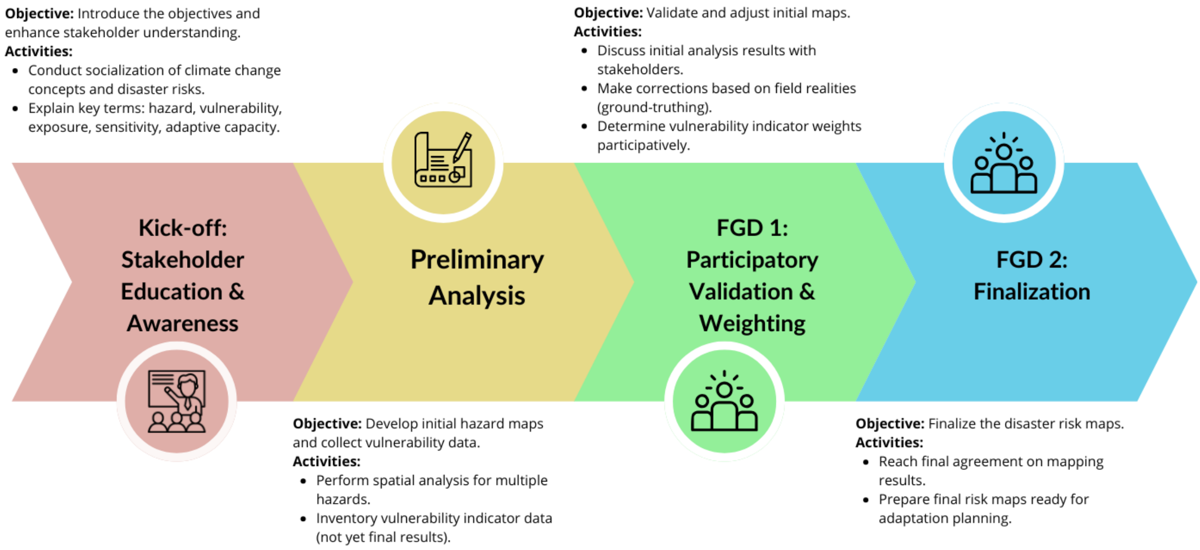

Figure 6. PPGIS framework flowchart for climate change multi-hazard risk mapping

3.5 Limitations and Future Directions

Although the results demonstrate the effectiveness of our participatory framework, several limitations remain. Hazard analysis relied on administrative village boundaries rather than hazard-specific delineations, potentially overlooking finer-scale dynamics. Vulnerability assessments were similarly constrained by available administrative data. This pragmatic choice, while enabling comprehensive coverage, may obscure household-level variations in risk. Future research should therefore prioritize finer spatial resolutions, such as land-use or building-level analyses, to capture micro-scale vulnerabilities [56,57]. Moreover, the proposed framework should be systematically tested in other regions and compared with alternative approaches to evaluate its robustness and adaptability across socio-ecological contexts. Such comparative applications will provide deeper insights into the transferability of participatory risk mapping frameworks, particularly in data-scarce environments where community engagement can compensate for limited secondary data.

Ultimately, this study demonstrates that integrating stakeholder-driven processes within PPGIS not only democratizes the production of disaster risk maps but also strengthens the legitimacy and adaptive capacity of local actors. The framework contributes a practical and transferable methodology for advancing climate resilience in Indonesia and offers significant potential for broader international application such as in the global south.

4. **Conclusion**

This study demonstrates that integrating secondary data, GIS-based spatial analysis, and stakeholder participation provides an effective approach to assessing and managing climate-related disaster risks in Pekalongan Regency. By applying a refined seven-level vulnerability classification, validated through stakeholder engagement, the analysis revealed distinct spatial patterns: flood hazards primarily affect northern riverine and coastal villages, while landslide threats are concentrated in the southern highlands. The findings underscore the crucial role of adaptive capacity, where socio-economic factors such as SME networks, disaster control infrastructure, and community programs mitigate vulnerability even in hazard-prone areas.

The main contribution of this study lies in the development of a multi-stage PPGIS framework that operationalizes participatory processes in risk mapping. In contrast to conventional GIS-only approaches, this framework involves stakeholders not only as data providers but also as validators and co-decision makers. This methodological innovation strengthens the credibility of spatial outputs, enhances local adaptive capacity, and produces risk maps that are both technically rigorous and socially legitimate. The framework also offers a transferable model for regions where reliable secondary data are scarce. From a policy perspective, the PPGIS framework provides a practical tool for local governments to integrate climate risk considerations into spatial planning and development strategies. Embedding stakeholder validation ensures that risk assessments align with community priorities, thereby increasing the legitimacy and effectiveness of adaptation measures such as ProKlim and Destana. The results emphasize the urgency of prioritizing coastal villages affected by land subsidence and southern mountainous districts at risk of landslides for targeted interventions, infrastructure investment, and resource allocation.

Future research should address the study's limitations, particularly the reliance on administrative boundaries that may obscure micro-scale risk dynamics. Applying the framework at finer spatial resolutions (e.g., building and household) and testing it across different regions will enable comparative evaluations of its adaptability and effectiveness. Such extensions will refine methodological accuracy and provide evidence for scaling participatory risk mapping into climate resilience policies. In conclusion, this study advances both methodological and practical knowledge by presenting a validated, participatory, and replicable PPGIS framework that strengthens disaster risk governance and supports inclusive, context-specific climate resilience strategies.

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