DETERMINING TSUNAMI DISASTER MITIGATION AREAS BASED ON THE PRESENCE OF MANGROVE ECOSYSTEMS

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Abstract. *The mangrove ecosystem plays a crucial role in tsunami disaster risk mitigation due to its capacity to attenuate wave energy and protect coastal areas. This study aims to develop a tsunami disaster mitigation concept based on mangrove ecosystem data by utilizing spatial analysis through Geographic Information Systems (GIS). The method employed is a quantitative descriptive approach, involving an overlay analysis between tsunami hazard data layers and mangrove distribution in Indonesia. This integration is expected to serve as a foundation for formulating effective and innovative mitigation action plans, emphasizing the strategic use of spatial data to support evidence-based planning. The evidence-based approach in this study provides a solid scientific foundation for policymaking in tsunami disaster mitigation, focusing on mangrove ecosystem recovery. Furthermore, the use of spatial data enables more accurate identification of priority areas, making the resulting policies more relevant to actual field conditions. The analysis indicates that integrating spatial data with empirical evidence is the key to producing more targeted, transparent, and accountable policies. This approach not only reduces reliance on assumptions but also enhances efficiency, equity, and sustainability in decision-making processes. With proper implementation, this model has the potential to generate more responsive, equitable, and effective tsunami disaster mitigation policies while supporting the long-term conservation of coastal environments.*

Keywords: *Environmental Recovery, Mangrove, Spatial Data,Tsunami Disaster Mitigation.*

1. INTRODUCTION

Tsunamis are among the natural disasters that pose significant threats to many coastal regions in Indonesia. These events are typically triggered by undersea earthquakes that cause vertical displacement of the seafloor. Analyzing tsunami hazards aims to understand the characteristics of both potential and historical tsunamis by considering the earthquake source, location, wave dispersion, propagation dynamics, and inundation height (BNPB, 2016).

Tsunamis are not unfamiliar to Indonesian society. From 1600 to 2007, Indonesia experienced a substantial number of tsunamis, approximately 90% of which were caused by undersea earthquakes, 9% by volcanic eruptions, and 1% by submarine landslides (Latief et al., 2000). During this period, 172 tsunami events were recorded, with more than 40% occurring in eastern Indonesia, particularly with epicenters in the Maluku Sea. One notable historical tsunami occurred in 1907 near Simeulue Island, Aceh Province. However, a more devastating event occurred on December 26, 2004, when a massive tsunami struck the coastal regions of the Indian Ocean, becoming one of the deadliest natural disasters in Indonesia's history. The earthquake that triggered this tsunami originated in the Indian Ocean, approximately 255 km from Banda Aceh, with a magnitude of 9.2 and a depth of around 30 km. The resulting waves not only devastated Aceh and Nias but also spread across ten countries bordering the Indian Ocean, including Malaysia, Thailand, Sri Lanka, the Maldives, Bangladesh, India, Kenya, Somalia, and Tanzania (Shaw, R., 2006). The impact was catastrophic, with over 200,000 fatalities in Indonesia alone. Across all affected regions, total recorded deaths reached 283,100 people, including 108,100 from Indonesia, while another 127,700 individuals were reported missing (Iemura et al., 2006). This tragedy highlighted the vulnerability of coastal areas to tsunamis and the immense destruction that can occur in a very short time, reinforcing the need for improved tsunami risk mitigation and planning, particularly through environmentally based strategies.

Mangrove forests—especially those with tall, complex root structures—play a significant role in attenuating tsunami wave energy. Research by Danielsen et al. (2005) demonstrated that coastal vegetation, including mangroves, can reduce the impact of tsunami waves. In forested areas of Tamil Nadu, India, damage was minimal or nonexistent, whereas unprotected beaches suffered severe destruction. Similarly, a study by Yanagisawa, Miyagi, and Baba (2010) found that mangrove forests significantly mitigated the effects of the 2009 Samoa earthquake and tsunami. The study revealed that wide mangrove belts could reduce tsunami inundation depth by up to 80%, providing empirical evidence that mangroves serve as effective natural barriers. Mangrove ecosystems can lessen the energy of waves from tsunamis and storms, though their protective efficacy depends greatly on location and forest density. If rehabilitation efforts fail to consider critical factors such as wave pathways or appropriate mangrove species, the restored areas may not significantly contribute to disaster risk reduction (Mazón et al., 2019).

The selection of conservation area locations involves land-use decisions influenced by multiple actors and factors. Multifactor analysis for site determination can be facilitated using Geographic Information Systems (GIS), though assessments often rely on the subjective judgment of individuals or institutions. Existing criteria for such decisions typically include physical, social, financial, and threat-related aspects (Nurrohmah et al., 2016). GIS plays a vital role in supporting the implementation of spatial decision-making by providing spatial data and enabling the analysis of interconnected factors in a geospatial context (M., 2022).

However, rehabilitation projects implemented in unsuitable locations or using inappropriate mangrove species may fail to optimize the ecological barrier function. For instance, restoring mangroves in areas not directly exposed to ocean waves or tsunamis may yield limited disaster-mitigation benefits. Rehabilitating areas solely to increase vegetation cover without considering strategic locations for risk reduction may result in mangrove zones that are ineffective in protecting coastlines (Spalding et al., 2014). It is common to find land areas intended for conservation being used for cultivation, either due to ignorance or intentional misuse by stakeholders (Nurrohmah et al., 2016). Restoring mangroves in locations directly along the main path of a tsunami wave can effectively reduce wave energy reaching inland areas. Conversely, prioritizing other areas without evaluating geographic risk factors will diminish the mangrove's role in disaster mitigation. Misguided rehabilitation efforts reduce the protective effectiveness of mangrove ecosystems (Thao et al., 2014). Therefore, an ecosystem-based disaster mitigation approach should be an integral part of mangrove rehabilitation projects. Such an approach ensures that the dual benefits of conservation and community protection are realized (Giri et al., 2011).

Due to increasing threats to mangrove systems, restoration efforts have been ramped up, yet outcomes are often disappointing due to insufficient long-term planning. Challenges include inappropriate site selection, limited project scope, and inadequate engagement with local stakeholders—all of which constrain the long-term success of restoration initiatives and prevent the recovery of functional mangrove forests. Successful restoration should result in mangrove forests that are expansive, diverse, functional, and self-sustaining, offering significant ecological and societal benefits (ICRI, 2018).

2. LITERATURE REVIEW

2.1 Innovation in Public Policy Formulation

Policy innovation is a crucial prerequisite that holds a strategic position for public sector organizations in supporting progress and sustainability toward the realization of good public policy governance. This aligns with the notion that every public sector organization is expected to undergo processes of adaptation and adoption in response to environmental changes (Sururi, 2019).

In the context of public policy, Geographic Information System (GIS) technologies such as ArcGIS enable governments to integrate, analyze, and visualize spatial data in ways that were previously unattainable. Technological innovations are more likely to be accepted and widely adopted when they offer clear advantages, are relatively easy to use, and are adaptable to existing institutional and operational contexts. ArcGIS meets these criteria by offering a wide range of tools for advanced geospatial analysis, map creation, and data modeling (Rogers, E. M., 2003).

ArcGIS provides a comprehensive platform for processing and analyzing spatial data, which supports evidence-based policy planning. For example, in spatial planning, ArcGIS facilitates the simultaneous analysis of land use, disaster risk, and infrastructure. Through its spatial analytical capabilities, ArcGIS supports the creation of thematic maps that are instrumental in problem identification, intervention planning, and policy evaluation.

In the environmental sector, ArcGIS is employed to monitor land-use changes, guide ecosystem rehabilitation, and mitigate disaster risks. Through spatial data modeling, policymakers can visualize the potential impacts of policies and conduct simulations to design more effective strategies. One example is mangrove rehabilitation. ArcGIS has been widely utilized to enhance communication and collaboration in decision-making processes, facilitate effective asset and resource management, improve workflow efficiency, and expand accessibility in targeted areas (Hartoyo et al., 2020).

2.2 Evidence-Based Policy (EBP) and Data Collaboration

The essence of Evidence-Based Policy (EBP) lies in the systematic collection and utilization of empirical data to guide the design, implementation, and evaluation of public policies, ultimately leading to more effective and accountable governance (Nutley et al., 2007). In the context of critical mangrove rehabilitation in areas with medium to high tsunami risk indices, EBP leverages various types of spatial data—such as base maps, administrative boundaries, critical mangrove distribution, and tsunami risk pathways—to design and implement policies that are both effective and measurable.

The base maps issued by the Geospatial Information Agency (Badan Informasi Geospasial, BIG) and the Ministry of Home Affairs (Kementerian Dalam Negeri, Ministry of Home Affairs of the Republic of Indonesia) play a crucial role in providing information on administrative boundaries across Indonesia. These maps serve as references for various governmental activities, development planning, natural resource management, and disaster mitigation efforts. Both institutions collaborate in managing and updating the administrative base maps, with BIG acting as the technical manager of geospatial data and Ministry of Home Affairs of the Republic of Indonesia serving as the data custodian (walidata), responsible for the ownership and governance of administrative boundary data.

BIG is responsible for compiling, managing, and disseminating base maps that include various geospatial elements such as topography, road networks, rivers, and administrative boundaries. These maps are developed based on Geographic Information System (GIS) theory, which supports spatial analysis using accurate geospatial data (Longley et al., 2015). This theoretical framework emphasizes that spatial data is a critical tool in supporting Evidence-Based Policy (EBP), wherein data-driven decisions are influenced by geographic conditions represented within the base maps.

The collaboration between BIG and Ministry of Home Affairs of the Republic of Indonesia in managing base maps and administrative boundaries is regulated by several key legal frameworks. Law No. 4 of 2011 on Geospatial Information mandates BIG as the primary institution responsible for managing national geospatial data, including the compilation of base maps as national references. Ministry of Home Affairs of the Republic of Indonesia, through the Directorate General of Regional Administration, acts as the data custodian for administrative boundary information. According to Presidential Regulation No. 9 of 2016 on the Acceleration of One Map Policy Implementation, Ministry of Home Affairs of the Republic of Indonesia is tasked with providing administrative boundary data that is integrated with BIG's base maps. Denhardt (2014) notes that one of the core principles of modern public administration is to "serve, rather than steer," underscoring the importance of transparency and accountability in governance, including the management of administrative boundary data. These administrative maps serve as a foundational reference for decisions related to budget allocation, authority distribution, and the management of population and resources in each region.

In disaster mitigation, administrative maps are essential for identifying areas vulnerable to hazards. Disaster mitigation theory (Smith & Petley, 2009) posits that risk mapping based on administrative data enhances the coordination of response efforts and facilitates the effective distribution of aid to the appropriate regions.

The concept of Tsunami Pathways is employed to identify, mitigate, and understand tsunami disaster risks, particularly within the context of disaster management policies in Indonesia as overseen by the National Disaster Management Agency (BNPB, 2013). Tsunami Risk Pathways refer to the potential routes or scenarios through which tsunami risk may unfold, including triggers, impact dissemination, and mitigation strategies. BNPB utilizes data from the National Tsunami Map, which identifies hazard-prone areas based on historical tsunami events, geological studies, and seismic data.

Meanwhile, BNPB's Tsunami Risk Index is a quantitative assessment used to evaluate tsunami risk levels based on three core components:

1. Hazard: Refers to the degree of physical threat posed by a tsunami, measured by the likelihood and intensity of potential tsunami events.
2. Vulnerability: Includes the socio-economic vulnerability of affected communities, such as poverty levels, population density, and the presence of critical infrastructure.
3. Capacity: Denotes the ability of communities and local institutions to mitigate disaster impacts, encompassing the availability of evacuation routes, early warning systems, and emergency preparedness.

This assessment integrates multiple data sources via the InaRISK platform, which aligns with global standards set by the United Nations Office for Disaster Risk Reduction (UNDRR). Theoretically, this index corresponds to the Pressure and Release model (Blaikie et al., 2003), which posits that disaster risk is not solely a function of natural hazards but also of social vulnerability and coping capacity.

According to the IRBI 2013 formulation, high-risk categories are defined by an index range of 17–24, while medium-risk categories fall within an index range of 4–16. Consequently, the classification of tsunami risk across districts and municipalities (Kabupaten/Kota) by region can be referenced in Table 1.

Table 1. Tsunami Risk Index by Region

Area	**Number of Regencies/Municipalities**		
	Moderate	**High**	**Total**
Balinusra	24	14	38
Jawa	12	23	35
Kalimantan	25	0	25
Maluku Papua	23	21	44
Sulawesi	23	39	62
Sumatera	16	29	45
INDONESIA	**123**	**126**	**249**

(Source: BNPB, 2013)

Mangrove ecosystems are transitional zones between land and sea that are highly productive and play a crucial ecological role in supporting various species of fish, birds, and other organisms. They also function as natural filters that help maintain coastal water quality (Odum, 1971). In Indonesia, critical mangroves refer to mangrove areas that have experienced severe degradation and require immediate rehabilitation efforts to preserve their function as buffer ecosystems (Ministry of Forestry, 2005). According to the 2021 National Mangrove Map, canopy cover density is classified into five categories based on Indonesian National Standard (SNI) 7717 of 2011:

1. Very dense mangroves (>90%)
2. Dense mangroves (70–90%)
3. Moderate mangroves (50–69%)
4. Sparse mangroves (30–49%)
5. Very sparse mangroves (<30%)

Based on this classification, mangroves categorized under canopy cover classes 4 and 5 are identified as critical mangroves, in line with the mangrove mapping conducted by the Ministry of Environment and Forestry (KLHK), where sparsely and very sparsely vegetated areas are designated as critical.

According to the spatial map released by KLHK in 2018, Indonesia had a total mangrove area of approximately 3.36 million hectares. Of this, around 1,817,999.93 hectares (52%) were in critical condition, while the remaining 1,671,140.75 hectares (48%) were considered to be in good condition. The spatial data sources used in this assessment include:

1. Technical Rehabilitation Plan Map for Watershed and Mangrove Areas (RTK RHL DAS) in Kalimantan, 2014
2. Mangrove Map of the Maluku Islands, 2017
3. Mangrove Distribution Map of Sulawesi Island, 2015
4. Mangrove Map of Java, 2013
5. Mangrove Map of Bali and Nusa Tenggara, 2016
6. RTK RHL DAS Map of Papua, 2014
7. Mangrove Map of Sumatra, 2014

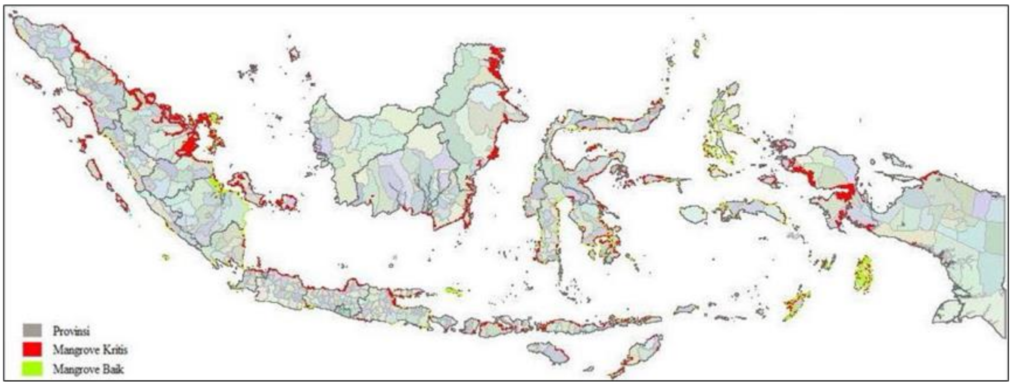

Figure 1. Mangrove Distribution Map of Indonesia
(Source: Ministry of Environment and Forestry (KLHK), 2018 (processed data))

3. RESEARCH METHODS

The research method employed in this study is spatial analysis using Geographic Information Systems (GIS) with a quantitative descriptive approach. A quantitative descriptive approach is used to describe phenomena by collecting and analyzing objectively measurable data. The purpose of this study is to identify and map areas classified as having high to moderate tsunami risk indices, along with tsunami hazard pathways, in regions with mangrove ecosystems categorized as either critical mangroves or healthy mangroves.

The data used in this study include the map of critical mangrove distribution provided by the Ministry of Environment and Forestry (KLHK), administrative boundary maps from the Geospatial Information Agency (BIG), and tsunami risk pathways and indices obtained from the National Disaster Management Authority (BNPB). These datasets were analyzed quantitatively to provide a more measurable understanding of coastal conditions.

By utilizing GIS, this study performs overlay operations of multiple map layers, including base maps of administrative boundaries, mangrove ecosystem maps, and tsunami pathways. This overlay process aids in identifying areas at high to moderate tsunami risk that also coincide with degraded mangrove ecosystems. Quantitative analysis was conducted to classify regions that contain mangrove habitats and those that do not. The results of the analysis are presented in tabular form, listing regencies and municipalities according to their respective tsunami risk index classifications. These findings aim to inform relevant stakeholders in determining priority areas for implementing disaster-mitigation-based mangrove rehabilitation programs..

4. RESULTS AND DISCUSSION

After processing the data using ArcGIS software, a base map of Indonesia was generated, displaying multiple layers of valuable spatial information. This map integrates several key elements: first, the distribution of critical mangrove areas, illustrated in red to indicate regions experiencing degradation or severe damage. Second, areas with healthy mangrove ecosystems are represented in green, reflecting regions with intact coastal vegetation capable of functioning as effective natural barriers.

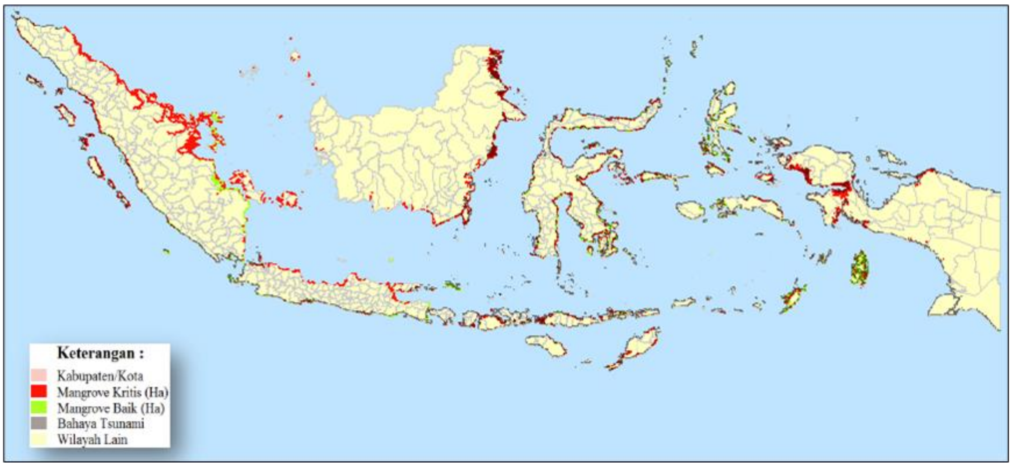

Figure 2. Map of Mangrove Distribution in Relation to Tsunami Hazards in Indonesia

In addition, the map is enhanced with an overlay of tsunami hazard pathways, depicted in gray, which indicate the potential routes of tsunami wave propagation and the coastal areas under direct threat. The integration of these three elements in a single visualization enables a more comprehensive analysis, allowing users to clearly observe the interaction between mangrove ecosystem conditions and the tsunami disaster risks threatening coastal regions.

Based on the analysis of the mapped data in the figure, the distribution of regencies/municipalities (Regency/City) can be summarized according to tsunami risk index classification, by region and the presence of mangrove ecosystems, as presented in Table 2.

Table 2. Tsunami Risk Index Based on the Presence of Mangrove Ecosystems

Area	Number of Regencies/Municipalities						
	Moderate Tsunami Risk	With Mangroves	Without Mangroves	High Tsunami Risk	With Mangroves	Without Mangroves	Total
Balinusra	24	20	4	14	13	1	38

Jawa	12	6	6	23	19	4	35
Kalimantan	25	16	9	0	0	0	25
Maluku Papua	23	17	6	21	19	2	44
Sulawesi	23	22	1	39	37	2	62
Sumatera	16	11	5	29	25	4	45
INDONESIA	**123**	92	31	**126**	113	13	**249**

1. There are 44 regencies/municipalities, comprising 31 with a moderate tsunami risk index and 13 with a high tsunami risk index, that do not possess mangrove ecosystems. Consequently, the implementation of ecosystem-based tsunami disaster mitigation through mangrove rehabilitation is not feasible in these areas due to the absence of natural mangrove habitats.

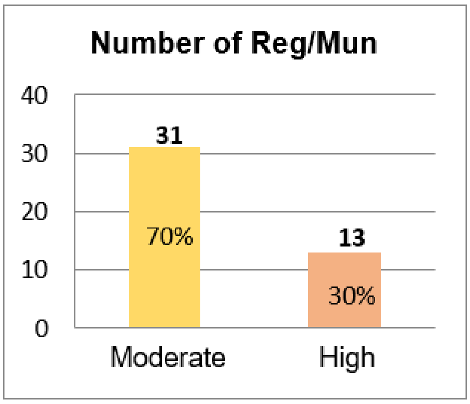

Figure 3. Comparison of the Number of Regencies/Municipalities with Moderate to High Tsunami Risk in Areas without Mangrove Ecosystems

2. There are 205 regencies/municipalities, comprising 92 with a moderate tsunami risk index and 113 with a high tsunami risk index that are characterized by the presence of mangrove ecosystems. This ecological condition enables the implementation of ecosystem-based tsunami disaster mitigation through mangrove rehabilitation, given the availability of natural mangrove habitats in these areas.

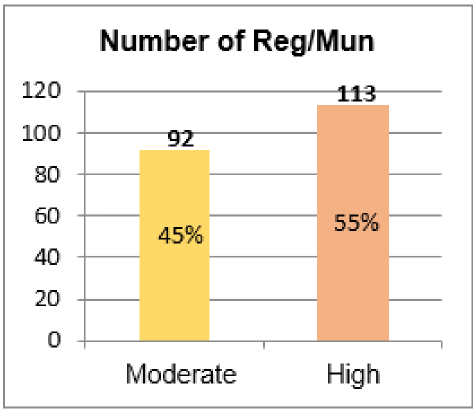

Figure 4. Comparison of the Number of Regencies/Municipalities with Moderate to High Tsunami Risk in Areas with Mangrove Ecosystems

CONCLUSION

The results of the study revealed that overlaying various data layers such as mangrove distribution maps, tsunami hazard pathways, and administrative maps provided a comprehensive overview of the interaction between mangrove ecosystem conditions and tsunami risks. The analysis led to three key findings: (1) Areas without

Mangrove Ecosystems; a total of 44 regencies/municipalities in Indonesia were found to have moderate to high tsunami risk indices but lacked mangrove ecosystems. This indicates that in these areas, mangrove-based disaster mitigation programs are challenging to implement due to the absence of supporting natural habitats. Some of the regencies/municipalities in this category include Southwest Aceh Regency, Lhokseumawe City, Bireuen Regency, and Aceh Jaya Regency; (2) Areas with Mangrove Ecosystems; a total of 205 regencies/municipalities with moderate to high tsunami risk indices were identified to have existing mangrove ecosystems, which enables the implementation of mangrove rehabilitation programs as a form of disaster risk mitigation. These regions hold potential for utilizing mangroves as natural barriers to reduce the impact of tsunamis. Examples include Sorong City, South Lampung, Kutai Kartanegara, and Tanggamus; (3) This study proposes the concept that mangrove-based tsunami disaster risk mitigation should be prioritized in regions where mangroves already exist. Therefore, disaster risk mapping that is integrated with mangrove ecosystem data offers a robust foundation for policymakers to design more effective mitigation strategies. The resulting maps can serve as visual tools for stakeholders in determining priority areas that require disaster-mitigation-oriented mangrove rehabilitation.

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