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Submission date: 08-May-2026 03:00PM (UTC+0700)
Submission ID: 2955861734
File name: REV_231025_1.docx (1.66M)
Word count: 5800
Character count: 34509

Integrating Modern Technology and Local Wisdom in Tsunami Early Warning Systems: Evidence from Serang Regency, Indonesia

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Received; Revised October 11, 2025; Accepted

Cite This Paper in the Following Citation Styles

(a): *[1] Bambang Pujiyono, Rusdiyanta, Arief Ruslan, Geri Suratno, Dwi Prijono Soesanto , "Integrating Modern Technology and Local Wisdom in Tsunami Early Warning Systems: Evidence from Serang Regency, Indonesia," Environment and Ecology Research, Vol. X, No. X, pp. XXX - XXX, 2025. DOI: 10.13189/XXX.2025.110XXX.*

(b): *Bambang Pujiyono, Rusdiyanta, Arief Ruslan, Geri Suratno, Dwi Prijono Soesanto (2025). Integrating Modern Technology and Local Wisdom in Tsunami Early Warning Systems: Evidence from Serang Regency, Indonesia. Environment and Ecology Research, X(X), XXX - XXX. DOI: 10.13189/XXX.2025.110XXX.*

Abstract Indonesia's coastal regions remain highly vulnerable to tsunami hazards, yet the effectiveness of existing early warning systems continues to be challenged by both technological and institutional limitations. In Serang Regency, Banten Province, the presence of modern technologies such as the Warning Receiver System (WRS-NG21) and early warning sirens has not been sufficient to ensure timely community response during emergencies. Weak coordination, inadequate maintenance, and limited community awareness have constrained their performance. At the same time, local wisdom-based communication systems—including mosque loudspeakers, traditional kentongan signaling, and social media networks—continue to play a central role in disseminating warnings at the grassroots level. This study examines how institutional roles and local wisdom can be effectively integrated to strengthen a community-based tsunami early warning system in Serang Regency. Employing a qualitative case study approach, data were collected from six coastal villages through semi-structured interviews, field observations, and document analysis. The findings reveal that integrating modern technologies with traditional communication practices creates a hybrid warning model that enhances both technical reliability and cultural legitimacy. The study identifies gaps in institutional coordination, insufficient standard operating procedures (SOPs), and the lack of local government support mechanisms as critical barriers to system sustainability. The results demonstrate that hybrid early warning systems can improve community trust, response speed, and overall disaster resilience. This study contributes theoretically by expanding the discourse on inclusive disaster governance, showing how local knowledge can complement formal institutional structures. Practically, the research proposes a framework for embedding indigenous practices within modern warning infrastructures, offering policy guidance for local governments in other tsunami-prone areas. Socially, it underscores the value of empowering communities as active agents in disaster preparedness and adaptive resilience.

Keywords Disaster Mitigation, Local Institutions, Local Wisdom, Tsunami Early Warning, Technology Integration, Serang Regency

1. Introduction

Since the enactment of Law Number 24 of 2007 concerning Disaster Management, Indonesia has made significant progress in disaster management. This progress includes strengthening national commitment, increasing institutional roles, and developing community preparedness through cross-sector partnerships. This

achievement has also strengthened Indonesia's position in the global disaster management forum [1].

However, the threat of disasters in Indonesia continues to increase in frequency and complexity. Data from the National Disaster Management Agency (BNPB) shows that between 2013 and 2022, there was a significant spike in the number of disaster events, with a peak in 2020 of 5,003 events. Although the number of fatalities tended to decrease post-2018, the ratio of victims to incidents still shows a high level of vulnerability. According to BNPB's Disaster Information Data (DIBI, 2023), more than 80% of Indonesia's territory is disaster-prone, and coastal communities are particularly exposed to tsunami threats.

This vulnerability is consistent with global findings. The IPCC (2022) highlights that coastal populations in Southeast Asia face compounding risks due to climate change, volcanic activity, and rapid urbanization. Tsunami disasters, such as the 2004 Indian Ocean tsunami and the 2018 Sunda Strait tsunami, illustrate the urgent need for stronger and more inclusive early warning systems.

Recent studies underline the importance of integrating modern technology with local knowledge systems in disaster risk reduction. A framework has been proposed in which indigenous knowledge, such as environmental cues and community practices, complements scientific tools and results in more trusted and effective responses ~~has been proposed~~ [2]. Similarly, cases in Africa and Asia; ~~concluding~~ conclude that hybrid approaches in early warning significantly reduce fatalities by increasing community trust and timely action [3]. In Indonesia, local wisdom such as religious norms, traditional communication (kentongan), and social cohesion ~~has~~ have been shown to enhance community preparedness when combined with technological systems [4][5].

The ~~following~~ data compares the number of incidents with the number of victims of disasters in Indonesia, as seen in Figure 1. This condition is a trigger for Indonesia to improve disaster management services.

This condition emphasizes the need to improve the quality of early warning systems and community preparedness, especially in tsunami-prone areas. Strengthening the early warning subsystem is very important to ensure that the community can receive disaster information in a timely, accurate, inclusive, and actionable manner. In this case, developing a Multi-Hazard Early Warning System (MHEWS) is urgently needed to deal with the dynamics of disaster risk that continues to grow [3]. One of the main challenges in developing this system is the limited technology and the vulnerability of communication systems in emergency conditions. Modern technologiesy, such as sirens, radio communications, and mobile phones, are often unreliable when there is a power outage or network disruption [6].

On the other hand, communities in disaster-prone areas often have local wisdom in the form of traditional disaster information delivery systems that have proven effective in emergency conditions. However, rapid modernization has resulted in this wisdom being increasingly marginalized. The local wisdom-based approach is considered more adaptive and deeply rooted in the social structure of the local community [2] [5].

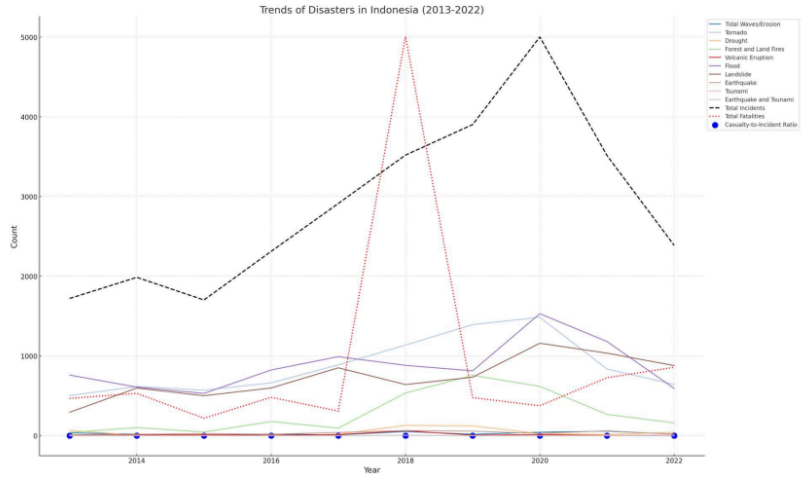

Figure 1. Ratio of Number of Disaster Incidents and Victims 2013-2022. Source: processed from DIBI BNPB and official BNPB publication infographics, 2023

The effectiveness of the early warning system is greatly influenced by the quality of the institutions that distribute the information. Local institutions play a strategic role in bridging modern technology and local wisdom practices. However, various studies show that the institutional capacity to manage and disseminate disaster information optimally, both at the district and village levels, is still limited [4] [7].

In this context, this study aims to analyze the role of institutions in utilizing local wisdom to increase the effectiveness of the tsunami early warning dissemination system. The focus of the study is on integrating technology and local wisdom ~~in~~ into an adaptive and inclusive institutional system, especially in disaster-prone areas in Serang Regency. [8] [9].

This context emphasizes that Serang Regency represents a relevant and urgent case study. Located along the Sunda Strait, Serang has experienced repeated tsunami threats triggered by Mount Anak Krakatau's volcanic activity. The December 22, 2018 tsunami killed 21 people and displaced nearly 5,000 residents in Serang alone (BNPB, 2023). While modern warning devices like sirens and WRS-NG units exist, they remain limited in coverage and reliability. On the other hand, local wisdom in the form of mosque loudspeakers, traditional tools, and community networks continues to function effectively, though it is increasingly marginalized by modernization.

Therefore, this study is timely and significant, as it analyzes how institutional roles and local wisdom can be integrated with technology to strengthen tsunami early warning systems. By situating the research in Serang Regency and drawing from broader comparative evidence, this study contributes to the discourse on building inclusive, sustainable, and community-rooted disaster resilience [2][3][4].

2. Materials and Methods

This study uses a qualitative approach to explore the institutional dynamics, conditions of early warning technology, and the role of local wisdom in the tsunami disaster mitigation system in vulnerable areas. A qualitative approach was chosen because it allows for a contextual understanding of the social and cultural realities that influence the effectiveness of early warning systems at the community level [10] [11]. This study was conducted in three sub-districts included in the tsunami-prone coastal areas in the Serang Regency, namely the Anyar Sub-district, the Cinangka Sub-district, and the Pulo Ampel Sub-district. The villages that were the locations for observation and interviews included Anyar Village (Anyar Sub-district), Bulakan and Karang Suraga Villages (Cinangka Sub-district), and Argawana, Salira, and Sumuranja Villages (Pulo Ampel Sub-district). These locations were ~~selected~~ purposively selected based on ~~the~~ their level of disaster vulnerability, early warning technology systems, and local wisdom practices still actively used by the community.

Data collection techniques involved a combination of direct observation of early warning infrastructure and evacuation routes, in-depth interviews with key stakeholders such as BPBD Pusdalops officers, village officials, disaster volunteers, and community leaders, and field surveys to document local practices in disaster mitigation. In addition, documentary studies were conducted on policy documents, preparedness activity reports, and standard operating procedures applicable at the regional level. The data's validity was assessed using a triangulation approach of sources and methods, which allows for comparisons between various field data and official documentation sources [12]. Participatory visualization and mapping were also used to capture the spatial dimensions of the early warning system and identify disaster-prone points in the research location. Data obtained through observation, interviews, and documentation were then analyzed through several stages. The initial stage of analysis involved ~~the process of~~ data filtration and validation, especially regarding information on the existence and function of available early warning technology.

Furthermore, the data was presented descriptively in the form of narratives and visual documentation, including spatial maps to illustrate the distribution of the warning system. Interview data were transcribed and analyzed using a thematic-inductive approach, following the coding procedure developed by Braun and Clarke [13]. This approach allows the identification of key themes such as inter-institutional relations, community involvement, and the integration of local wisdom in early warning systems. The methodology used in this study is in line with the community-based disaster study approach, which is widely used in the literature because it can describe the complexity of the relationship between institutions, socio-culture, and local capacity in the context of disaster risk management Thus, this approach not only explains the factual conditions in the field but also provides a basis for formulating evidence-based policy recommendations that are sensitive to the local context.

3. Result

3.1. Overview of Tsunami Disaster Risk in Serang Regency

Serang Regency, located in the northern and western parts of Banten Province, includes 29 sub-districts, 326 villages, and 19 islands, with 37 villages located on the coast. This area ~~has an area of~~covers 1,467.35 km², around 15.72% of the area of Banten Province, making it the third largest regency after Lebak and Pandeglang. Geographically, Serang Regency is bordered by the Java

Sea, Cilegon City, and Serang City to the north; Lebak and Pandeglang Regencies to the south; Tangerang Regency to the east; and Cilegon City and the Sunda Strait to the west.

The coastal areas of Serang Regency, especially from Anyar Beach to Cinangka, as well as the northern coastal areas covering the Java Sea and Banten Bay, are vulnerable to tsunami disasters. This potential threat is mainly caused by the volcanic activity of Mount Anak Krakatau in the Sunda Strait. Based on DIBI-BNPB 2023 data, Serang Regency experienced a tsunami on December 22, 2018, triggered by Mount Anak Krakatau's activity. This disaster caused 21 fatalities, 2,395 people were injured, 4,820 people were displaced, and 41 houses and 19 kiosks were damaged.

Realizing the above conditions, the Serang Regency Government is committed to handling the tsunami disaster outlined in the Serang Regency RTRW 2011-2031. This commitment is reflected in the determination of efforts to protect tsunami-prone areas through 7 (seven) main programs, namely determining the boundaries of tsunami-prone areas, building a Tsunami Early Warning System (TEWS), building tsunami retaining walls on coastlines at risk, planting mangroves along the coastline to reduce the force of tsunami water, controlling development in tsunami disaster areas, building evacuation routes and gathering points as evacuation spaces, and conducting coaching and outreach programs for the community in tsunami-prone areas.

Serang Regency is considered to be in the High-risk class for tsunami disasters. The Tsunami Disaster Risk Map for Serang Regency is shown in Figure ~~1-2 below~~.

Tsunami disaster risk conditions, including the tsunami early warning system in each village/sub-district, need to be considered to ensure optimal utilization and sustainability of tsunami early warning information dissemination sirens in the future. In addition, sociological conditions and community preparedness capacity also need to be considered to ensure that the management of tsunami early warning information dissemination sirens runs well at the village/sub-district level. There is ~~A~~a description of the six villages in Serang district that are at risk of a tsunami disaster, namely:

3.1.1. Anyar Village

According to the Dukcapil-Ministry of Home Affairs Statistics for the first semester of 2023, Anyar Village has 7,714 people with the highest population density among other IDRIP locus villages, 2,858 people/km². Vulnerable groups, such as toddlers, the elderly (1,205 people or 15.62%), and people with disabilities (5 people), require special attention in disaster preparedness. This village is at high risk of tsunamis, with 96.92% of its area (261.68 hectares) exposed, consisting of medium (63.26 hectares) and high (198.42 hectares) risks.

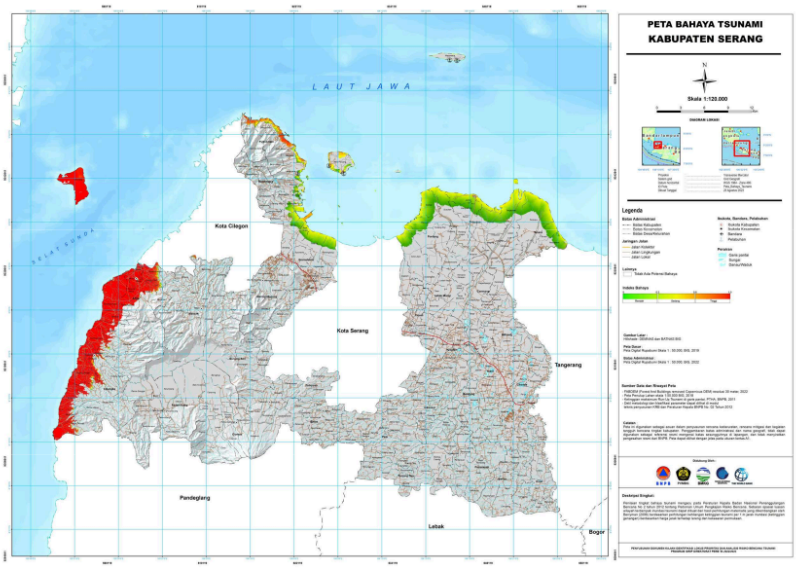

Figure 2. Tsunami Disaster Risk Map of Serang Regency. Source: Tsunami Disaster Risk Assessment of Serang Regency in 2023, BNPB

Anyar Village does not yet have a permanent tsunami siren, but the Indonesian Red Cross (PMI) provides a portable siren with a range of 1 kilometer. The commitment of the community and volunteers to maintain this siren was driven by the experience of the tsunami on December 22, 2018, which did not cause any fatalities or damage to houses or fishing boats. In terms of preparedness, PMI, the village government, and BNPB have provided disaster preparedness training, evacuation, and the use of early warning. Anyar Village has a disaster volunteer team inaugurated through a Village Head Decree, although it does not yet have an early warning SOP. Evacuation sites include SMK Negeri 1 Anyar, Anyar District Office, and Kadu Dago Village, Sindang Karya Village.

3.1.2. Bulakan Village

Bulakan Village has the smallest population among the IDRIP loci, namely 4,417 people, with a density of 653 people/km² in an area of 6.77 km². A total of 659 residents (14.92%) are classified as vulnerable, and 14 people are disabled. This village has a moderate tsunami risk, with a low-risk area of 6.18 hectares and a moderate-risk area of 505.53 hectares. Although it has not experienced a tsunami in the last 20 years, Bulakan Village does not yet have an early warning siren. However, the community and village governments have stated the importance of the siren and are committed to maintaining it if it is built.

In preparedness, BPBD has provided socialization regarding evacuation routes, and signs are now installed in various locations. Bulakan Village does not yet have a disaster volunteer team or early warning SOP. If a tsunami occurs, the community plans to evacuate to the hills or mountains around the village.

3.1.3. Karang Suraga Village

Karang Suraga Village has 6,300 people with a density of 694 people/km² in an area of 9.08 km², making it the largest village among the IDRIP loci. A total of 968 residents (15.37%) are classified as vulnerable, and 16 people are disabled. Almost the entire village area (97.40% or 884.38 hectares) is potentially exposed to a tsunami, with the greatest risk being in the moderate class (879.20 hectares), so categorizing this village is categorized as having a moderate risk.

Karang Suraga Village does not yet have an early warning siren despite being exposed to a tsunami. Early warning information was distributed through WhatsApp Group (WAG), but the community considered the siren very important, considering due to the village's location facing the Sunda Strait. In preparedness, BPBD has provided socialization regarding evacuation routes and signs. These signs direct residents away from the coast to higher areas, although the village does not yet have a disaster volunteer team or early warning SOP.

3.1.4. Argawana Village

Argawana Village has the largest population among the IDRIP locus villages in Serang Regency, namely 7,876 people, with a density of 1,847 people/km² in an area of 4.27 km². As many as 16.19% of the population (1,275 people) are classified as vulnerable, and 13 people are disabled. The area potentially exposed to a tsunami is only 10.83% (46.21 hectares), with low risk (40.11 hectares) and medium (6.10 hectares), so the risk of a tsunami disaster in this village is relatively low.

Argawana Village does not yet have an early warning siren for tsunamis, but the community supports its existence to improve safety. Community preparedness is quite good thanks to disaster socialization by the Government, the business world, and volunteers. Although the SOP for early warning is not yet available, the community uses mosque loudspeakers and evacuation signs installed through the IDRIP 2023 program to direct residents to evacuation sites in Banyuwangi Village.

3.1.5. Salira Village

Salira Village has 5,063 inhabitants with a density of 1,469 inhabitants/km² in an area of 3.45 km². As many as 13.98% of the population (708 people) are classified as vulnerable, with no disabled residents. The area potentially exposed to a tsunami reaches 15.30% (52.73 hectares), with most of which are it in the medium risk class (46.45 hectares), so the tsunami risk level is categorized as MEDIUM. This village does not yet have an early warning siren, and information is conveyed through social media. The community welcomed the plan to build a siren and is committed to maintaining the device's functioning. Community preparedness is quite good, supported by disaster socialization from BPBD and Destana facilitators and disaster facility assistance from PT. Indonesia Power. Evacuation sites are directed to SMP Negeri 1 Pulo Ampel as a Temporary Evacuation Site (TES) and Kampung Salira Waringin as the Final Evacuation Site (TEA). However, there is no standard early warning SOP.

3.1.6. Sumuranja Village

Sumuranja Village has 4,972 inhabitants with a density of 1,709 inhabitants/km² in an area of 2.91 km². The vulnerable population is 15.51% (771 people), and there are two people with disabilities. The tsunami-exposed area of 10.73% (31.22 hectares) is relatively small with moderate risk (18.37 hectares), so the tsunami disaster risk is categorized as MEDIUM. Early warning information is delivered through WhatsApp Group and the InaRISK application. The community supports the construction of early warning sirens for the safety of residents. Preparedness is considered quite good with the presence of a disaster volunteer team, socialization from BPBD and BNPB, and evacuation signs from the IDRIP program and Serang Raya University. Although

evacuation routes are available, Sumuranja Village does not yet have a TES, TEA, or early warning SOP.

3.2. Description of Serang Regency Early Warning System

Organization, installation, and testing of early warning systems are part of preparedness as regulated in Law No. 24 of 2007 concerning Disaster Management. This system aims to inform the Government and the public to anticipate disasters and prepare for emergencies. Effective early warning provides information on potential disasters and supports rescue, evacuation, protection of vulnerable groups, and management of refugees, both in the alert and emergency response phases. This information is also used in contingency plan operations.

According to BNPB Regulation No. 4 of 2022, there are five main activities in early warning: observation of disaster symptoms, data analysis, decision-making, dissemination of information, and community action. Observation and analysis activities prioritize applied technology, such as the central Government's implementation. However, BPBD, through Pusdalops, still plays a role in supporting the observation and analysis of local disasters.

BMKG is responsible for the observation of earthquakes and tsunamis according to Presidential Regulation No. 93 of 2019. This early warning system is based on detecting the primary wave (P) before the damaging secondary wave (S). Earthquake information is delivered in less than 3 minutes through platforms such as INA-TEWS and InaRISK, including earthquake magnitude, tsunami potential, and shake map, using tools such as seismometers, accelerographs, and GPS.

Serang Regency already has a disaster information and early warning system that combines technology and local wisdom, although it is still focused on earthquakes and tsunamis. Some of the early warning infrastructure that has been built in Serang Regency are:

a) WRS-NG21, which BMKG will assist in 2021. WRS-NG is a communication tool from BMKG used to disseminate tsunami warnings to intermediary institutions, including BPBD/Pusdalops. This device supports Pusdalops's two main functions, namely receiving and disseminating warnings and directions to communities at risk. The placement of WRS-NG at the Serang Regency BPBD office accelerates the delivery of information on potential tsunamis or earthquakes according to the SOP for early warning and evacuation.

b) In the early warning communication mode, Pusdalops BPBD Serang Regency has used various ~~communication~~ modes for internal communication of Pusdalops personnel and ~~to communicate with~~ for external communication with other parties. Internal communication mode usesusing 2 RIG radios where 1 belongs to BPBD, and one belongs to BNPB, which uses a VHF frequency channel at 150.430 MHz. To communicate with BPBD Banten Province, Pusdalops uses a RIG radio with a frequency of 150.430 MHz connected to a repeater belonging to BPBD Banten Province. PLN electricity sources and generators operate various communication devices and provide backup electricity sources.

c) Early warning transmitter system: Currently, ~~there is~~ a transmitter tower is located in the Pusdalops office complex. It is a 4-inch monopole tower ~~with a height of~~ 15 meters tall and functions as an internal BPBD radio communication antenna. This tower was procured in 2013 and built on government land.

d) Dissemination sirens were used for early warning information and tsunami evacuation, whereas until September 2023, there were two units of tsunami early warning sirens. The sirens do not overlap with the location of the Tsunami Early Warning Information Dissemination Siren Development activities through the IDRIP program. Based on their condition, the two units still functioning apart from the BPBD sirens have earthquake detectors at the Pusdalops office. The sirens in Serang use GSM signals, and the cell phone is the control button.

The list and distribution of existing siren placement locations can be seen in Figure 3 below.

Figure 3. Dissemination technology and placement of sirens in Serang Regency

3.3. Institutional Description

Institutions involved in the dissemination of tsunami early warnings in Serang Regency can be described as follows:

a) The Meteorology and Geophysics Agency (BMKG) is an institution that has the technology to obtain initial data on earthquake events.
b) The National Disaster Management Agency (BNPB) is a government institution that is the coordinator for handling disaster events.
c) BPBD, through the Pusdalops unit, receives disaster event information directly from BMKG. This information is received through technological devices owned by the Serang Regency BPBD.
d) Pusdalops then conveys the tsunami early warning information through available technology such as Sirens, WA Groups, Call Centers, and Social Media Groups. This WA Group includes local government organisations, the private sector, and communities interested in disasters. Dissemination of this information is aimed at communities at the village level with the potential for tsunami disasters.
e) Village Government: The central manager conveys early warning information and organises responses at the village level.
f) Disaster Preparedness Group, ~~Disseminating~~disseminates early warning information through various communication channels.
g) Community leaders/religious leaders, as well as respected and trusted parties, have a significant influence in conveying messages related to disasters.
h) Karang Taruna, assist~~sing~~ in disseminating early warning information through social media and other communication tools.

Information institutions' centralisation and capacity to disseminate information can be described based on these institutions. First, this institution forms an early warning information institution and dissemination centre that operates continuously with trained personnel according to agreed national standards and international benchmarks. This institution will utilise disaster risk knowledge and hazard information developed on the MHEWS Platform to produce early warning system products based on impact and early action that can be accessed by all communities of all ages, genders, and abilities, including in remote areas.

Second, strengthening dissemination capabilities. This institution strengthens existing capabilities to disseminate MHEWS information messages and supports increased preparedness capacity. This effort will consider existing capabilities to provide warnings of hazards, including and starting from the provinces affected by the 2018 disasters. This includes replacing and upgrading existing communications equipment, computer networks, and information and communication technology platforms.

In some cases, geographic coverage will be expanded; in others, outdated technology will be replaced. This strengthening will be carried out primarily for Pusdalops at the district/city level. Equipment will be selected based on local specifications and include technical and other considerations to enable integration into existing systems and ease of maintenance and operation. By combining local wisdom with modern efforts, the Serang Regency community can improve its preparedness and mitigation for tsunamis or other earthquakes.

Third, iInstitutions at the village level need to work together synergistically to improve the effectiveness of early warning dissemination. This collaboration can involve: a). Structured coordination through village deliberations involving all institutions to discuss disaster mitigation and response strategies; b). Local risk mapping: communities create maps of disaster-prone areas and evacuation routes; and c).~~dan~~ Integrated simulations involving all institutions in evacuation simulations so that each party understands their role during a disaster.

With a strong village institutional role, communities can be better prepared for earthquakes and tsunamis to minimise the risk of loss of life. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

4. Discussion

The findings from six coastal villages in Serang Regency show that tsunami vulnerability remains high, while the capacity of early warning systems is limited. Modern devices such as WRS-NG21 and early warning sirens exist but are constrained by technical issues and limited coverage. In contrast, traditional methods like mosque loudspeakers, kentongan, and WhatsApp groups remain effective in reaching communities. This duality highlights the urgent need to integrate modern technologies with culturally embedded communication systems.

For example, Anyar and Karang Suraga villages demonstrated that portable sirens and social media groups can effectively support community preparedness. However, most villages still lack standardized operating procedures (SOPs) and permanent siren installations, leaving gaps in reliability. Similar to findings in Pekalongan's tidal flood management [14], Serang's case shows that local institutional collaboration and community participation are critical in ensuring early warning messages are acted upon. Comparable patterns were also observed in Japan [8], where disaster-resilient communities were built through strong local institutions and culturally rooted practices.

The study also reveals that institutional capacity at the village level is underdeveloped. Disaster volunteer teams,

~~where~~ when present, often lack training and coordination with official agencies. This reduces the effectiveness of communication chains during emergencies. A study in Aceh highlighted the same issue, showing that volunteer networks significantly improve preparedness when supported by local governments [4]. In the Philippines, integrating indigenous warning systems with formal disaster agencies has been reported to reduce delays in community evacuation [2].

Integrating technology and local wisdom is another critical aspect. Traditional cues, such as changes in animal behavior and natural signs, are deeply trusted by local communities. When combined with modern sensors and digital communication, these cues can enhance the credibility and speed of warnings. Similar integration has been found in African flood-prone regions, where blending local environmental knowledge with modern monitoring improved community trust in early warnings [3][15]. In Indonesia, integrating indigenous practices into formal disaster preparedness has been shown to strengthen resilience, such as in the case of Anak Krakatau [16], and in Mentawai Islands where local wisdom is embedded in disaster mitigation strategies [17]. Likewise, empirical lessons from Tiworo illustrate that local wisdom is a specific knowledge system that enhances community adaptation to natural hazards [18]. In Nepal, incorporating traditional practices into disaster education has also been shown to strengthen adaptive capacities [19].

From a technological standpoint, innovations such as recurrent neural networks have been successfully applied in tsunami tide prediction, supporting the Indonesia Tsunami Early Warning System [20]. Recent developments in digital twin models based on Bayesian inference further highlight the potential for real-time decision-making in tsunami early warning [21]. These findings complement earlier reviews showing that integrating scientific and local knowledge in early warning systems leads to more trusted and effective disaster risk reduction strategies [3].

Overall, Serang Regency's early warning system is evolving toward a hybrid model that leverages both modern and traditional mechanisms. However, gaps in infrastructure, institutional capacity, and SOP development remain significant challenges. These findings align with broader international evidence that disaster governance becomes more sustainable when technological innovation is embedded within local cultural and institutional contexts.

5. Conclusions

This study shows that integrating modern technology with local wisdom can significantly strengthen tsunami early warning systems in Serang Regency. The novelty lies in demonstrating that hybrid strategies linking scientific tools such as WRS-NG21 and sirens with traditional communication and knowledge are both practical and culturally relevant. Comparisons with studies in Japan, Aceh, the Philippines, and Africa confirm that similar hybrid approaches enhance resilience and inclusivity. Strengthening institutional coordination at the village level and formalizing SOPs remain urgent tasks. Embedding local knowledge within technological systems creates disaster governance that is more inclusive, sustainable, and resilient to future tsunami risks.

6. Recommendations

Based on the findings of this study and comparisons with similar research globally, several recommendations can be made for policymakers and disaster management stakeholders in Serang Regency and other tsunami-prone regions:

a) Institutionalize Hybrid Strategies – The integration of modern technology with local wisdom should be formalized as a core disaster preparedness strategy. Evidence from Japan [8], Aceh [4], and the Philippines confirms that hybrid approaches strengthen community trust and accelerate responses [2].

b) Strengthen Village-Level Institutions – Local disaster volunteer teams require continuous training and structured coordination with BPBD and BMKG. Comparative studies show that strong community institutions significantly enhance preparedness and resilience.

c) Develop and Standardize SOPs – Formal operating procedures for early warning dissemination should be established at the village level. This ensures consistency and reliability, especially in areas with limited siren coverage or unstable communication networks.

d) Invest in Inclusive Communication Networks – Investments should not only focus on advanced tools like WRS-NG21 but also grassroots-level channels, including mosque loudspeakers, kentongan, and digital groups. Studies from Africa show that inclusive communication improves both access and trust in warning systems [3].

e) Embed Local Wisdom in Disaster Education – Traditional environmental cues and practices should be documented, validated, and included in disaster education for schools and community training. Evidence from Nepal shows that combining digital education tools with cultural knowledge enhances intergenerational resilience [19].

Acknowledgements

Thank you to all researchers who helped in preparing this scientific article well. Hopefully, this research will be able to answer the problems that occur in Karimun Regency in overcoming the problems that occur. Thank you also to the BNPB for providing data and fully contributing to answering the research researched and raised in this scientific article.

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