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MULTI-SCENARIOS TSUNAMI HAZARD AND EVACUATION ROUTES USING SEISMIC DATA IN PACITAN BAY, INDONESIA

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ABSTRACT: On the southern coast of Java Island, Pacitan Bay is densely populated and faces Java Trench, making it susceptible to trapping tsunami waves. This geographical setting, characterized by a dense population, bay morphology, and proximity to the trench, increases the risk of a tsunami. Despite the increase in such risk, comprehensive mitigation measures are lacking in the region. Addressing this gap requires the development of effective strategies, advanced modeling, and robust evacuation plans to enhance community resilience. Therefore, this study aimed to model tsunami scenarios using seismic data and assess evacuation routes to identify potential bottlenecks. Numerical modeling was adopted to generate tsunami propagation and inundation. The Delft3D software, based on the Shallow-water Equations, was used for tsunami propagation modeling, while *Hloss* calculations were adopted for inundation. Subsequently, evacuation routes were generated using network analysis from hazard zones to designated shelters. Approximately 1500 random locations were generated across the hazard zone, and line-to-line overlay analysis was conducted to determine the frequency of route segment usage, thereby enabling the identification of bottlenecks. This study examined three tsunami scenarios based on fault parameters, with Scenario 1 having significant threats characterized by a 6.28-meter run-up, short evacuation times, and extensive inundation. Furthermore, the results showed varying levels of impact across sub-districts. The analysis of evacuation routes indicated varied travel times, signifying potential bottlenecks at Jendral Gatot Subroto Road, Sinoboyo-Plumbungan Road, and roads leading to Shelters 3 and 5. The Tsunami model predicted scenarios of varying severity, assisting in the identification of bottlenecks in evacuation routes.

Keywords: Tsunami, Hazard, Evacuation, Pacitan Bay, Java Trench

1. INTRODUCTION

Indonesia is positioned at the convergence of several tectonic plates, serving as a crucial case study for exploring the intricate relationship between geological processes and natural disasters. This unique geographical setting [1,2] not only amplifies seismic challenges but also positions the country to be a focal point for global understanding of natural disasters [3,4]. With the archipelagic topography characterized by an active subduction zone, Indonesia offers a compelling model for seismic investigations worldwide.

Focusing on the southern coast of Java Island, which lies above an active subduction zone where the Indo-Australian plate subducts beneath the Eurasian plate [5,6], this study aims to build upon previous reviews while addressing existing knowledge gaps. The segmentation of the subduction zone into distinct sections such as the Sunda Strait-Banten, West Java, and Central Java-East regions [7] presents a nuanced understanding of the seismic threat landscape. Past seismic events, particularly the devastating tsunamis in Banyuwangi and Pangandaran in 1994 and 2006 [8], show the urgent need for comprehensive disaster mitigation strategies in the region.

Java Island serves as the Indonesian most densely populated landmass [5,6], with the southern coast hosting significant urban centers, including Banten, Pangandaran, Cilacap, and others. Given the vulnerability of the regions to tsunami threats [9,10] a thorough examination of risk and preparedness strategies becomes necessary. The proximity to the subduction zone, along with the presence of seismic gaps [19,20], further complicates the task of accurately projecting hazard, specifically in funnel-shaped bays such as Pacitan Bay, which face a high risk of megathrust earthquakes [21,22].

While previous reviews have explored various aspects of tsunami along the southern coast of Java, including evacuation procedures [11], vulnerability [21], risk [22], and hazard [23,24] assessments, an integrated method that combines seismic data with evacuation routes to assess the effectiveness of current disaster mitigation plans is significantly absent. The integration is essential not only for understanding but also for enhancing community resilience against future tsunami threats.

This study aims to fill the existing knowledge gap by introducing a comprehensive tsunami model that uses seismic-record calibrated numerical inundation modeling. The model is complemented by an in-depth evaluation of evacuation routes to identify potential bottlenecks, thereby offering valuable insights into the effectiveness of existing current evacuation strategies. This study not only contributes to the knowledge concerning tsunami in Java but also proposes a methodological framework that can be adapted and applied to other regions.

The remainder of this investigation is organized as a section, which provides an urgent overview, followed by the methodology. This section elaborates on the data and methods used for tsunami modeling and route analysis. The results and discussion section presents the results and engages with existing literature. Finally, the conclusion section synthesizes the total results of the study.

2. RESEARCH SIGNIFICANCE

This study addressed a crucial gap in existing literature regarding tsunami modeling in Pacitan by integrating seismic data and deriving evacuation model based on network analysis. Using numerical modeling with the Shallow-water Equations and Delft3D-Flow software [28], the investigation predicted wave heights and run-ups in Pacitan. The analysis was expected to contribute to the development of coastal community resilience in Java, provide insights for disaster management, offer valuable recommendations for policymakers, and present a practical method to minimize the impact of the potential tsunami on Pacitan Bay.

3. METHODS

3.1 Data Collection

This study relied on secondary data obtained from scientific reports, official sources, and spatial data from Pacitan Regency institutions. These included administrative maps of Pacitan Sub-districts and earthquake records from the United States Geological Survey (USGS) (earthquake.usgs.gov) [29]. The data also consisted of earthquake slip deficit, national bathymetric with a spatial resolution of 6 arc-seconds (±180 meters) obtained from the National Geospatial Information Agency (Badan Informasi Geospasial, BIG) website, slope inclination maps, coastal boundaries, evacuation shelters from local government, and road network. All the datasets adequately fulfill the requirements for tsunami propagation simulation, tsunami inundation simulation, and network analysis of evacuation routes.

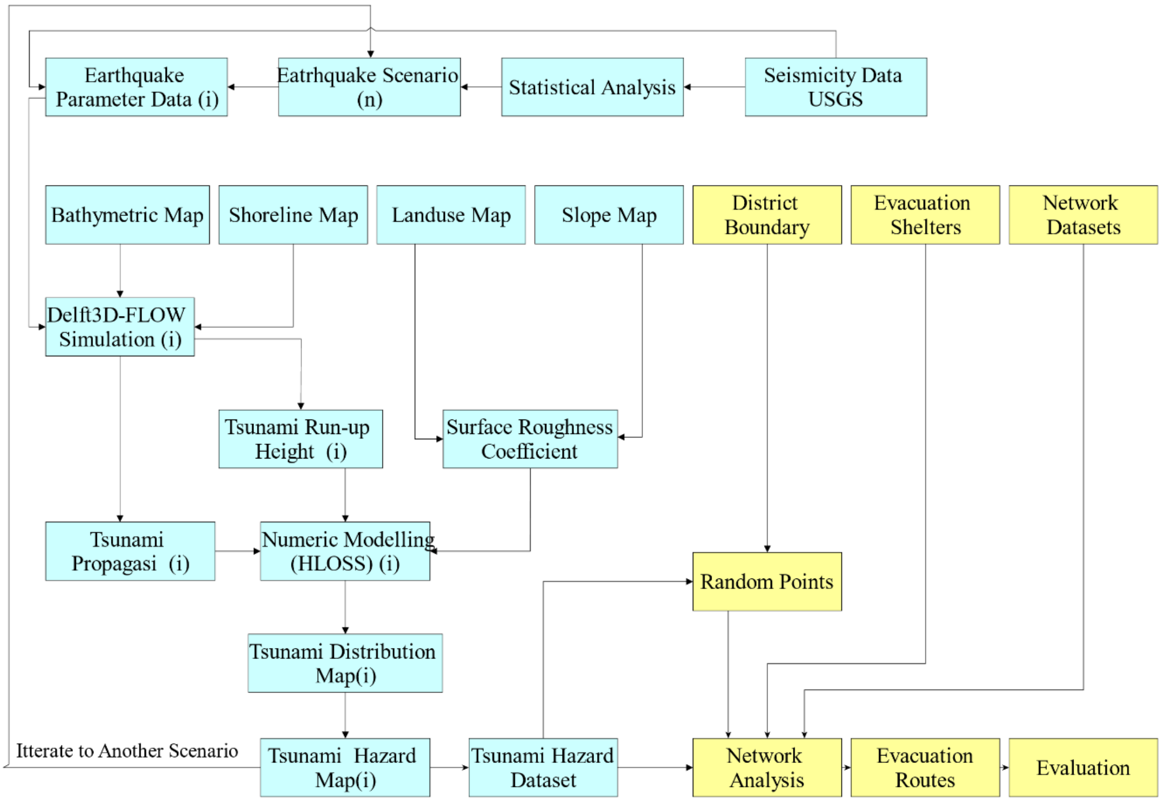

Fig. 1 Research Framework

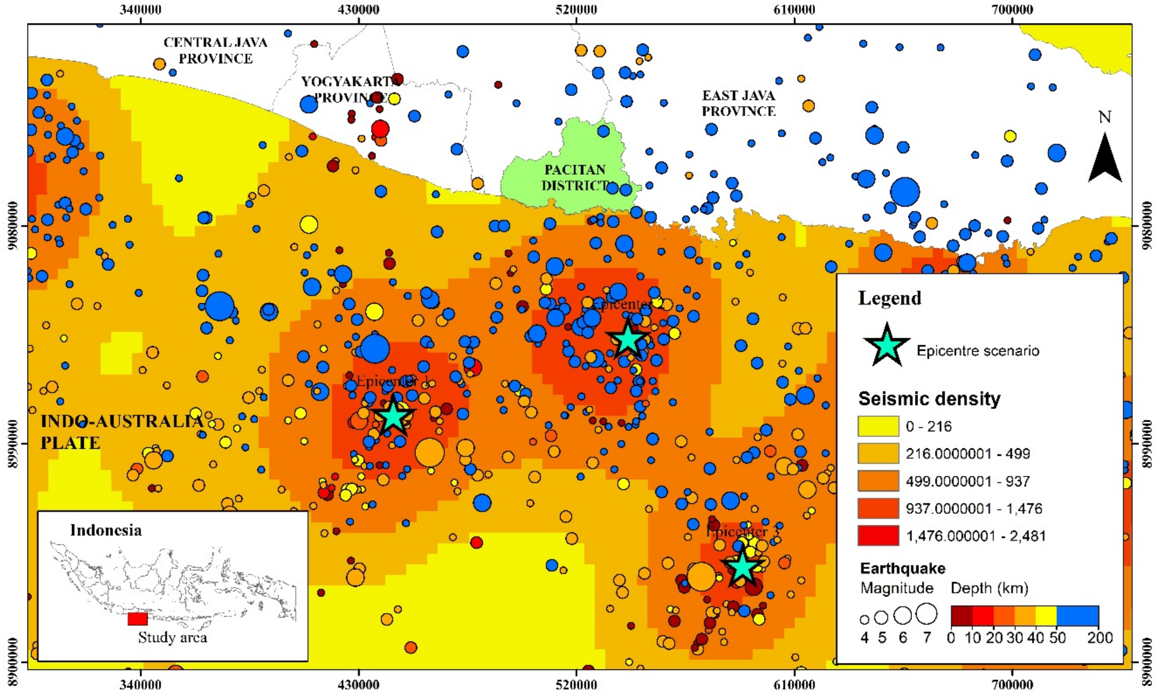

Fig. 2. Seismic data from 1900-2023 in the study area (left); earthquake density contour (middle); the epicenters of three earthquakes were used in constructing three tsunami scenarios (own elaboration from USGS earthquake data [29]).

Table 1. Fault parameters of modeling scenarios

Parameters	Scenario 1	Scenario 2	Scenario 3
Magnitude (Mw)	8.0	7.5	8.0
Latitude (°)	-9.026865	-8.738950	-9.588418
Longitude (°)	110.493893	111.375484	111.807951
Depth (km)	10	10	10
Width (km)	24	9.5	60
Length (km)	60	40	180
Strike (°)	280	282	280
Dip (°)	10	10	10
Slip/Rake (°)	90	90	90
Dislocation/Slip (m)	5	5	5

3.2 Study Framework

The initial methodological phase (Figure 1) consisted of data preparation, aiming to create comprehensive datasets as the foundation for the subsequent analysis. Geographic Information System (GIS) software was adopted for accurate georeferencing and seamless integration of datasets. The step provided a unified spatial framework for various elements of the study.

Tsunami propagation modeling was conducted, covering the process of digitizing the coastal line, delineating sea-land boundaries using ArcGIS, converting shapefiles to X and Y coordinates, and defining the grid context in Cartesian coordinates. Bathymetry data was interpolated into the grid context, and the simulation was set for 6 hours with a time step of 0.1 minutes. To parameterize the model, seismic parameters, including depth, magnitude, and location were used for tsunami-triggering process. The epicenter points were generated based on seismic data density, considering the magnitude as the weight from 1900 to 2023, obtained from USGS (earthquake.usgs.gov). Approximately three earthquake scenarios were generated from the data to trigger tsunami (Table 1).

The table presented fault parameters for three seismic scenarios, each characterized by varying magnitudes, locations, and dimensions. While

Scenarios 1 and 3 shared a magnitude of 8.0 with similar strike and dip angles, they differed significantly in geographical coordinates and fault dimensions. Scenario 2, with a magnitude of 7.5, was distinguished by the smaller width and length compared to others. Despite such variations, all scenarios maintained consistent depths of 10 km, slip/rake angles of 90°, and dislocation/slip of 5 m, indicating uniform movement mechanisms across fault characteristics.

High-resolution bathymetric data derived from the BIG website was seamlessly integrated into the computational model. This detailed underwater terrain data was used to accurately model tsunami waves traveling from the seismic source toward the coastline. The simulations were conducted using the Shallow-water Equations adopted in the Delft3D-Flow software [30,31].

Table 2. Physical parameters of modelling

Parameter	Value
Constant:	
Gravity (m/s^2)	9.81
Water density (kg/m^3)	1025
Air density (kg/m^3)	1
Roughness: Manning coefficient (uniform)	0.024
Viscosity: Horizontal Eddy viscosity (m^2/s)	1

$$Hloss = \left(\frac{167\ n^2}{\mathrm{H}_0^{1/3}}\right) + 5 \sin S \qquad (1)$$

The subsequent step consisted of modeling tsunami inundation, where Berryman's height loss (*Hloss)* formula (Equation 1) was adopted to assess the level of the inundation on land [32]. *Hloss* facilitated the calculation of height loss over horizontal distances from the inundation points. The key physical parameters, including fault parameters for tsunami generation and roughness coefficients based on the work of Berryman [32], were specified (Table 2). $Hloss$ was computed for every 1-meter inundation distance (n) based on the surface roughness coefficient (S), tsunami wave height at the coastline (H_0), and the surface slope in degrees.

For Evacuation Routes Modeling, network analysis was adopted in the ArcGIS environment, using a network dataset created from road network data. The speed attributes assigned to different road types were integral to this modeling process. Specifically, neighborhood streets were assigned a velocity of 20 km/hour to show the lower capacity and speed limits. In contrast, major roads were designated with a higher velocity of up to 60 km/hour to accommodate faster movement, assuming evacuees would use motorcycles or cars.

To simulate the movement of the exposed population, 1500 random points were generated around the bay, with each point representing an individual attempting to evacuate. Using the road network, the simulation calculated the closest routes from each random point to one of the five designated shelters, based on local government data [16,25]. This method not only considered the spatial distribution of the exposed population but also integrated the real-world road network dynamics, including varying velocity on road types [25]. The results of evacuation routes were then spatially joined with road network data to count the frequency of passing routes and create the density map.

4. RESULTS AND DISCUSSION

4.1 Tsunami Model

This study assessed three tsunami scenarios based on fault parameters, as shown in Table 3. Each might provide essential insights into potential tsunami results, and in Scenario 1, the maximum run-up reached a significant 6.28 meters, indicating the potential for severe coastal inundation. Additionally, the distance from the epicenter to the bay was substantial at 111 kilometers, contributing to the extensive affected area of 743.23 hectares. The situation raised concerns regarding the potential impact of Scenario 1, as it enhanced the risk of widespread coastal inundation and substantial damage (Figure 3). With the scenario, the tsunami would only take 28 minutes to reach the bay. In Scenario 2, although the maximum run-up was lower at 3.5 meters, the time to reach the bay was relatively short, taking only 26 minutes. The distance from the epicenter was also shorter than in Scenario 1, at 65 kilometers, signifying a faster method. However, Scenario 2 had a less impactful tsunami, and the affected area covered a considerable 390.85 hectares.

Table 3. The results of tsunami modeling scenarios

Results	Scenario 1	Scenario 2	Scenario 3
Maximum run-up (m)	6.28	3.5	3.6
Time to reach the bay (minutes)	28	26	35
Distance from the epicenter to the bay (km)	111	65	171
Affected areas (ha)	743.23	390.85	405.98

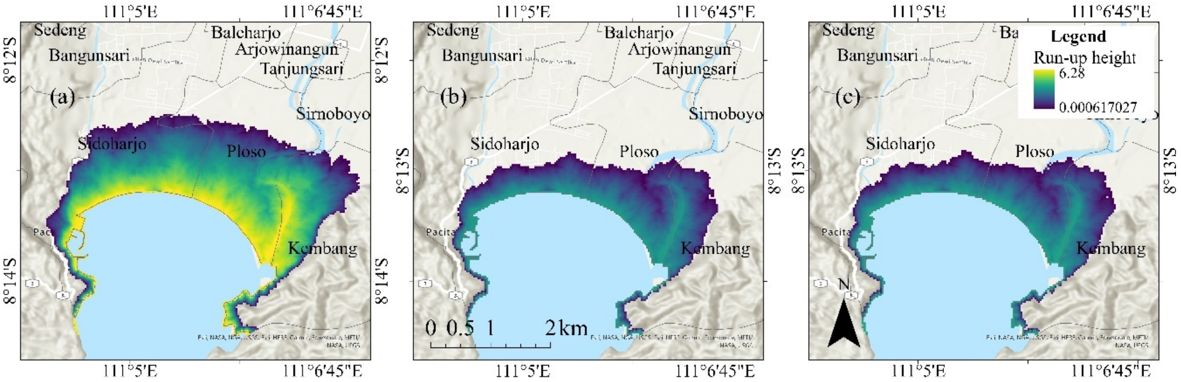

Fig. 3. Inundation model of tsunami scenarios. (a) Scenario 1, (b) Scenario 2, (c) Scenario 3.

Scenario 3 had characteristics that differentiated it from others. Despite a moderate maximum run-up of 3.6 meters, the time to reach the bay was 35 minutes, longer than both Scenarios 1 and 2. Additionally, the distance from the epicenter was the greatest among the three scenarios (171 kilometers), potentially reducing the immediate impact on the coastal region. The affected region, covering 405.98 hectares, was significant but slightly less than Scenario 2. Analyzing these fault parameters provided crucial information for assessing the severity, velocity, and spatial extent of potential tsunami events, guiding effective disaster response and management strategies tailored to each scenario's unique characteristics.

Figure 3 presented the inundation levels in the ranges of low, moderate, and high. In Scenario 1, the sub-district of Sidoharjo experienced a high total inundation, with 299.28 hectares classified as high impact. Scenarios 2 and 3 also had varying levels of impact across sub-districts, showcasing the spatial distribution of potential inundation. The sub-district of Sirnoboyo in Scenario 1 had the minimum exposure, totaling only 0.09 hectares of inundated region. Similarly, in Scenarios 2 and 3, the sub-districts of Sirnoboyo and Kembang consistently showed minimal exposures, with relatively low total inundated regions. The regions were significantly different, suggesting lower impacts in the event of tsunami, making them potentially less vulnerable.

4.2 Evacuation Route

Analyzing tsunami evacuation times showed variations in travel time from the origins of evacuees to safe places (shelters) and signified potential bottlenecks on certain roads. This data was essentially for optimizing evacuation plans and making informed decisions regarding infrastructure and logistics. The distribution of travel times derived from routes analysis for tsunami evacuation was specifically significant (Figure 4), ranging from 0.6 minutes to 9.0 minutes.

Each travel time corresponded to a specific frequency, indicating how often that duration occurred. This detailed breakdown was crucial for understanding the variability in evacuation durations and providing valuable insights into the efficiency and potential congestion within routes (Figure 5). The presence of multiple peaks in the frequency distribution suggested distinct patterns or modes of evacuation, signifying the complexity and heterogeneity in the time it took for individuals or groups to reach safe places.

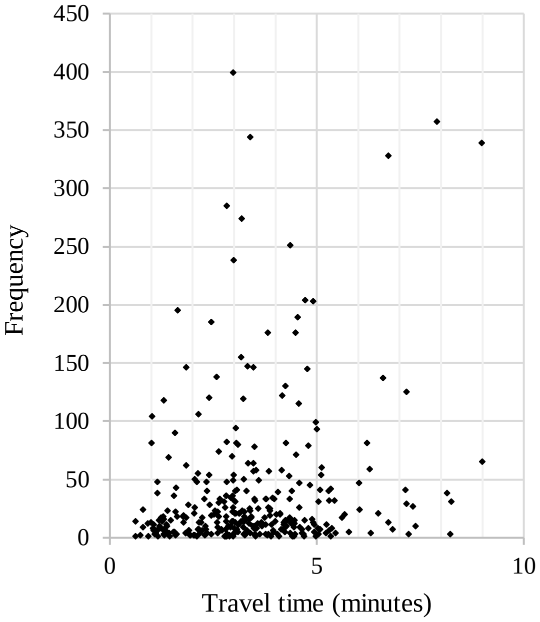

Fig. 4. Travel time frequency to reach evacuation shelters.

The thorough analysis of travel times showed potential bottlenecks in certain evacuation routes, particularly those leading to shelters, excluding Shelter 1 (Figure 5).

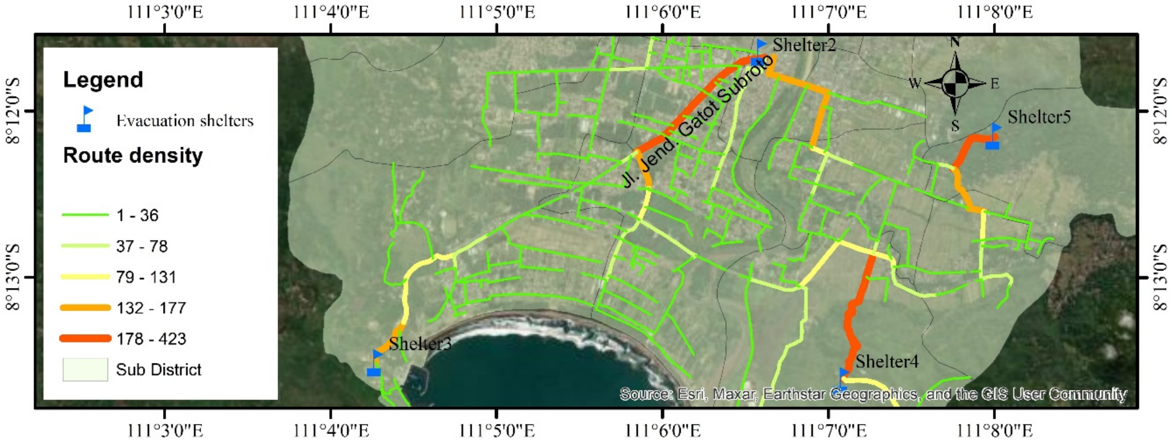

Fig. 5. Evacuation route analysis

Specifically, Jend. Gatot Subroto Road, Sinoboyo-Plumbungan Road, and the unnamed road leading to Shelters 3 and 5 served as vulnerable routes with high-density traffic. These identified potential bottlenecks might experience congestion during evacuation, impacting the efficiency of the total plan. Therefore, routes management and more attention to these specific sections were necessary during evacuation procedures.

4.3 Discussion

Tsunami modeling indicated that Scenario 1 presented a significant threat, characterized by a 6.28-meter run-up, short evacuation time, and an impact zone covering 743.23 hectares. The level of the threat signified the necessity for specialized disaster response strategies. This study showed the crucial role of the model in forecasting, mitigation [36], and emergency planning [37], while also identifying unaddressed evacuation bottlenecks and scenarios [11,21,23]. However, limitations arose from the scarcity of historical tsunami records on the southern coast of Java and oversights such as coastal structures and bathymetry variations, which might affect accuracy. The study evacuation simulations, assuming consistent population behavior without considering response time variability or dynamic road network changes, limited the real-world applicability.

Future investigations should leverage real-time data on population and road conditions to enhance analysis robustness, including transportation system data and social media inputs [38]. Furthermore, integrating dynamic coastal conditions and bathymetric changes into tsunami modeling could improve accuracy [39]. Addressing variations in human behavior during evacuations through an agent-based model [40] and engaging local communities in locally tailored evacuation strategies, such as using local institutions in evacuation management, were suggested to enhance disaster preparedness.

5. CONCLUSION

In conclusion, this study adopted a hydrodynamic tsunami propagation model to explain three scenarios of varying severity. Scenario 1, characterized by a maximum run-up of 6.28 meters, posed a significant threat with a 28-minute time frame to reach the bay and a vast affected region covering 743.23 hectares. Scenario 2 had a moderate impact, while Scenario 3, with a longer time to reach the bay and a greater distance from the epicenter, suggested potential mitigation measures. Inundation analysis identified sub-districts with various levels of exposure, while evacuation modeling uncovered potential bottlenecks, particularly in routes leading to shelters, signifying the importance of tailored disaster management plans. The comprehensive routes analysis further informed strategies to optimize tsunami evacuation plans and address congestion challenges, thereby enhancing the total effectiveness of disaster response measures.

6. ACKNOWLEDGMENTS

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