# Spatial analysis of tsunami hazard based on numerical models and seismicity data in Pacitan Coastal Areas, Indonesia

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**Abstract.** The Pacitan Regency, located on the southern coast of Java adjacent to the Indian Ocean, is susceptible to tsunami disasters due to its geographical location. Therefore, mitigation efforts are essential, including the development of tsunami modeling and evacuation strategies. While previous studies have combined these aspects, simulations involving simultaneous evacuation of both coastal residents and tourists remain scarce. This research aims to simulate the evacuation of coastal residents and tourists during various tsunami scenarios resulting from seismic activities, with the goal of formulating an optimal evacuation model. The study employs a tsunami propagation model utilizing numerical methods based on Shallow Water Equations and HLOSS calculations in the Delft3D-Flow software to assess tsunami hazards. The results from the modeling indicated that the highest tsunami run-up height was recorded at maximum 8.78 meters. Various tsunami inundation models are generated using the software and combined as composites to produce comprehensive tsunami hazard maps. This integrated approach provides valuable insights into optimizing evacuation procedures for both local inhabitants and tourists, thereby enhancing disaster preparedness and response strategies in The Pacitan Coastal Areas of Indonesia.

## 1 Introduction

Indonesia, a nation marked by its picturesque coastal landscapes, is also a region highly vulnerable to geological hazards, particularly tsunamis [1]. The southern coast of Java, the country's most populous island, stands at the confluence of tectonic forces, where the Indo-Australian plate subducts beneath the Eurasian plate [2, 3]. This subduction zone is segmented into three sections: the Sunda Strait-Banten segment, the West Java segment, and the Central Java-East Java segment [4]. Although historically characterized by lower seismicity compared to its Sumatran counterpart, recent devastating events in 1994 and 2006 in Banyuwangi and Pangandaran [5], respectively, have underscored the region's latent seismic potential.

The southern regions of Java, including Banten, Pangandaran, Cilacap, Kebumen, Kulon Progo, Bantul, Gunung Kidul, Pacitan, Trenggalek, Tulungagung, and Banyuwangi, are particularly susceptible to tsunamis [6]. This vulnerability arises due to the proximity of these areas to the subduction zone and the presence of seismic gaps – active subduction zones that have experienced little seismic activity for extended periods. Among these vulnerable areas, the Pacitan Regency, situated along the Indian Ocean, is especially at risk due to its direct exposure to megathrust activity [7].

Previous studies exist on modelling the tsunami hazard in Pacitan, such as [1, 8, 10]. The objective of this study is to address a research gap by integrating historical seismic data from the neighboring areas of Pacitan. This data has the potential to improve the parametrization of tsunami models and provide a wide range of precise tsunami propagation scenarios. The objective is to enhance the precision and dependability of hazard estimates for Pacitan by refining tsunami models.s This paper aims to provide a tsunami hazard model based on numerical tsunami modeling. Employing the Shallow Water Equations, a numerical method for shallow water wave simulations, and utilizing the Delft3D-Flow software, this study seeks to predict tsunami wave heights and run-up in the Pacitan Regency.

# 2 Methods

## 2.1 Data Collection

Secondary data, sourced from literature studies, official reports, and relevant institutions in the Pacitan Regency, form the basis of this research. These data include administrative maps of Pacitan sub-districts, Earthquake Slip Deficit Data in South East Java, National Bathymetric Data 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, Sentinel Images, Coastline Boundaries, Tsunami Evacuation Points, and demographic data.

## 2.2 Research Framework

In the initial phases of the research (Figure 1), a meticulous process of data preparation was undertaken to harness the necessary information for the study. Diverse datasets, ranging from administrative maps to seismic and bathymetric data, were collected and subjected to a rigorous digitalization process. The goal was to create a comprehensive and coherent database that could serve as the foundation for the subsequent analyses. To achieve this, Geographic Information System (GIS) software was employed, ensuring not only the accurate georeferencing of the datasets but also their seamless integration. This step was pivotal in providing a unified spatial context for the various elements of the study, laying the groundwork for precise modeling and analysis.

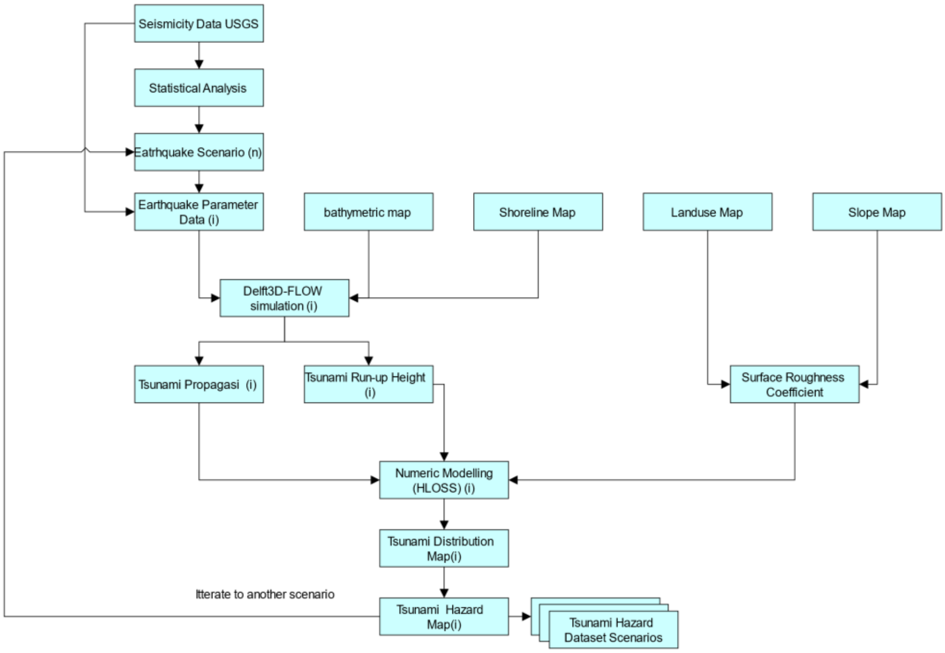

**Fig. 1.** Research Framework.

Subsequently, seismic data, specifically the Earthquake Slip Deficit Data, played a vital role in identifying potential earthquake sources within the subduction zone. These data points, reflecting crucial seismic parameters such as depth, magnitude, and location, were meticulously integrated into the tsunami modeling process. By incorporating these seismic data points, the research team was able to simulate realistic earthquake scenarios, setting the stage for accurate and reliable tsunami predictions. The precision of these initial conditions was paramount, as they significantly influenced the outcomes of the subsequent simulations.

Moreover, high-resolution bathymetric data obtained from the BIG website was seamlessly integrated into the computational model. This detailed underwater terrain data proved invaluable in understanding the complex behavior of tsunami waves as they traveled from the seismic source toward the coastline. By incorporating this information, the research team enhanced the accuracy of their predictions, capturing the intricate dynamics of wave propagation over varying underwater landscapes.

The integration of seismic and bathymetric data laid the foundation for the numerical simulations conducted to predict tsunami wave propagation across the study area. Leveraging the Shallow Water Equations implemented within the sophisticated Delft3D-Flow software [11, 12], the research team was able to conduct precise simulations. These simulations facilitated the calculation of essential parameters, including wave heights, velocities, and directions, as the tsunami waves approached the coastline. This step was pivotal in understanding the potential impact of the tsunami waves, enabling the researchers to assess the areas at risk and formulate effective mitigation strategies.

To quantify the extent of tsunami inundation on land, the research team employed the Hloss formula derived from Berryman's work. This formula enabled the calculation of the loss in tsunami height over horizontal distances from the inundation points. By applying this formula, the researchers determined the areas susceptible to inundation, providing critical insights into the vulnerable regions. GIS tools were instrumental in translating these calculations into detailed inundation maps. These maps not only visualized the extent of potential damage but also served as practical guides, highlighting vulnerable areas and evacuation points. This comprehensive approach, integrating data preparation, seismic analysis, bathymetric insights, numerical simulations, and inundation mapping, formed the backbone of the study, ensuring a robust and detailed analysis of tsunami risks in the study area.

### 2.3 Tsunami Modeling

Tsunami inundation modeling is a critical aspect of this study. To determine the spread of tsunami inundation on land, the concept of "hloss" was employed. Hloss represents the loss in tsunami height per 1-meter horizontal distance from the inundation point (inundation height). Berryman [13] developed a mathematical formula to calculate Hloss based on the distance to the slope and surface roughness. The formula derived from Berryman's work was utilized to estimate the extent of tsunami inundation on land. The research process involved several computational steps to model tsunami inundation accurately.

## 3 Results and Discussion

The study employed a hydrodynamic model using Delft3D software based on the Shallow Water Equations to simulate tsunami wave propagation. The hydrodynamic model utilized a Single Grid configuration, covering the seismic source generating the tsunami in the subduction zone to the coastline, encompassing an area of 98,718 km². To ensure the accuracy of the simulation, the researchers determined a simulation runtime of 6 hours, with data storage intervals of 0.1 minutes. Three observation points were established to monitor wave propagation: Station 1 on the coastline, Station 2 outside Pacitan Bay, and Station 3 on the Soge Beach in Ngadirojo Sub-District. Station 2 was strategically placed outside the bay to assess wave height before entering the bay and the influence of surrounding cliffs on tsunami wave propagation. Station 3 was located on the open coast of Soge Beach, providing a basis for comparing tsunami run-up heights on both bay and open coastlines.

The results from the modeling efforts indicated that the highest tsunami run-up height was recorded at Station 3, measuring 8.78 meters, followed by 5 meters at Station 1 and 2.1 meters at Station 2. The tsunami waves took approximately 38 minutes to reach the Pacitan coastline from the earthquake's epicenter, covering a distance of 242 km. Additionally, Station 2 observed initial wave arrival at 33 minutes, while Station 3 experienced it at 36 minutes, covering a distance of 241 km from the earthquake source to the observation point.

The simulations illustrated the widespread impact of the tsunami waves. Fig. 2 -4 showed that the affected areas extended to Pacitan and Kulon Progo, Trenggalek, Tulungagung, Blitar, and Malang. However, the study's primary focus remained on the tsunami risk along the Pacitan Sub-District coastline.

Furthermore, the simulation revealed the non-linear behavior of tsunami waves. Wave heights varied due to changes in underwater topography (bathymetry) and the presence of underwater features such as seamounts. The simulation captured the transformation of the wave direction at the 30-minute mark, redirecting towards the Kulon Progo region.

The evaluation of the tsunami inundation zone was crucial. Berryman's formula (Hloss) was employed, considering slope inclination, tsunami height at the coastline, and surface roughness coefficient. The roughness coefficient was derived from land use data in the Pacitan Sub-District. Using a scenario of an 8.0 magnitude earthquake, tsunami run-up height was set at 5 meters at the coastline. Based on the classification in accordance with Perka No. 2 BNPB Year 2012, the tsunami hazard map classified areas into three categories: low, moderate, and high risk. The areas in red indicated the most significant impact, while the yellow areas presented moderate potential. Green areas represented the lowest tsunami wave impact. The affected areas in the Pacitan Sub-District included Sidoharjo Urban Village, Ploso Urban Village, and Kembang Village, as depicted in Fig. 2 - 4.

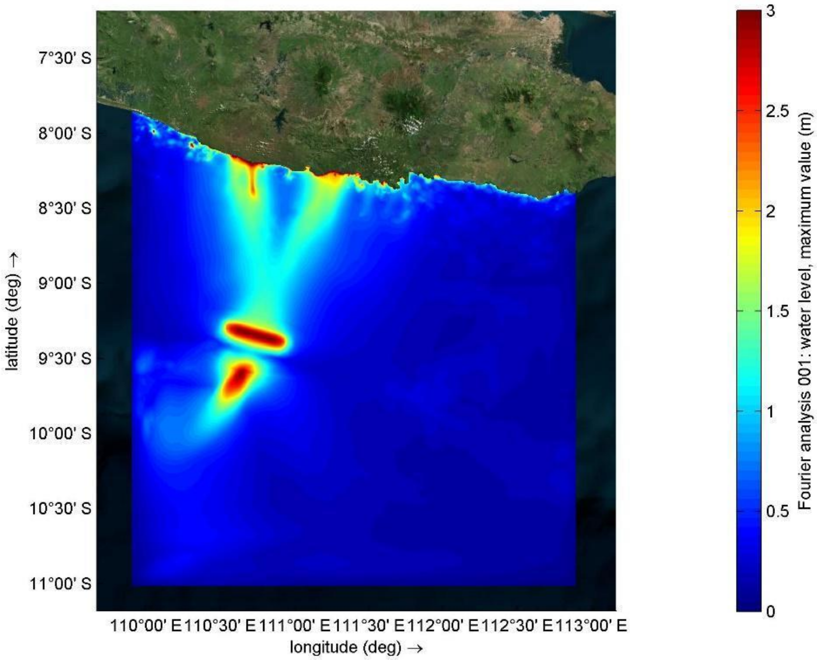

**Fig. 2.** Tsunami Scenario 1.

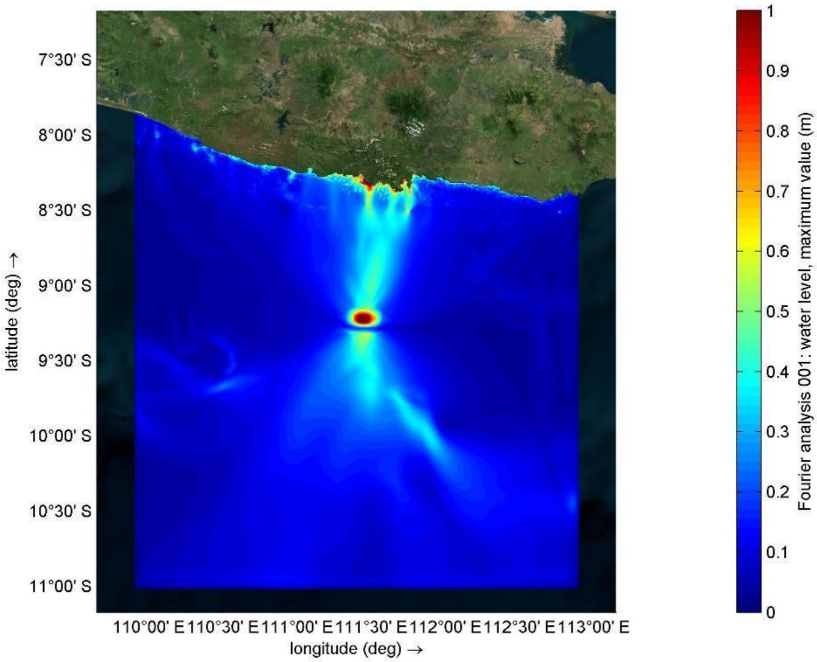

**Fig. 3.** Tsunami Scenario 2.

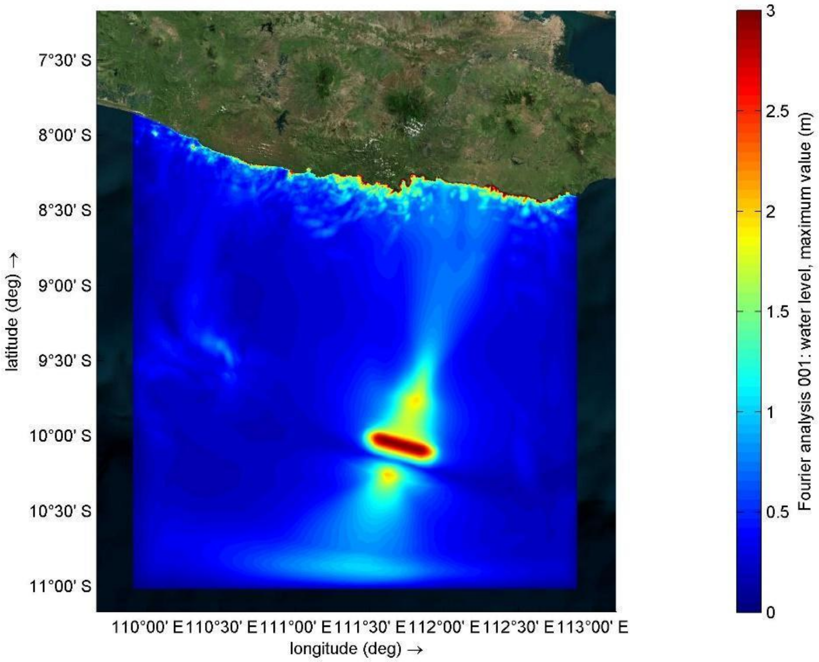

**Fig. 4.** Tsunami Scenario 3.

## 4 Conclusion

The results highlighted the significant vulnerability of the Pacitan Sub-District to tsunamis, with wave heights reaching up to 8.78 meters in certain areas. The findings provided valuable insights for disaster preparedness and mitigation efforts, emphasizing the importance of comprehensive evacuation planning, early warning systems, and community education to minimize the potential impact of future tsunamis in the region.

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