

Application of numerical simulation method integrated SfM-UAV to tsunami hazard map in Jailolo



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Tsunamis pose a significant threat to the Jailolo coastal area in North Maluku, Indonesia, because of its proximity to the Maluku Sea subduction zone, where seismic activity has historically triggered destructive waves. This study aims to map tsunami hazards in the Jailolo coastal area by integrating the Structure-from-Motion (SfM) photogrammetry method with numerical calculations. The SfM photogrammetry method involves using an unmanned aerial vehicle (UAV) to produce digital elevation model (DEM) data in the form of digital terrain model and digital surface model, as well as orthomosaic data. In addition, tsunami wave propagation simulation modelling was carried out using the Cornell Multi-Grid Coupled Tsunami computational program, with input data including Manning's coefficient data and fault parameters. The aerial photography resulted in DEMs with a vertical accuracy of LE90 of 0.15 metres and an orthomosaic with a horizontal accuracy of CE90 of 0.5 metres. The tsunami simulation revealed tsunami waves reaching 5.8–17.4 metres, with a hazard zone of approximately 119.31 hectares and an inundation distance of about 700 metres from the coast. The affected areas include settlements, agriculture and mangrove forests. In conclusion, the integration of UAV-based SfM photogrammetry and numerical simulations effectively produces high-precision tsunami hazard maps.

Contribution: This study provides a significant contribution to disaster mitigation and evacuation planning by providing an accurate and efficient method for mapping tsunami hazards. The precise data can support decision-making in high-risk coastal areas such as Jailolo.

Keywords: photogrammetry; COMCOT; hazard; tsunami; Jailolo.

Introduction

Tsunamis are commonly described as significant vertical sea-level fluctuations resulting in huge wave formation. Globally, seismic activity, which depends on variables such as magnitude, epicentral depth and plate movement dynamics, causes most tsunamis. So, tsunamis are more significant after earthquakes with a strong vertical mechanism, whether normally or backwards, compared to earthquakes of the same size with a shear mechanism (Pranantyo 2020). Tsunamis are natural hazards that are always dangerous for those who live along the coast. Although they rarely occur, tsunamis are a force to be reckoned with because of their enormous damage potential. As the events in Palu in 2018 demonstrated, volcanic activity and landslides can cause tsunamis.

North Maluku represents a region characterised by a significant risk of tsunami occurrence. If an earthquake measuring eight on the Richter scale occurs at a depth of 10 kilometres within the Maluku Sea subduction zone, significant tsunami threats exceeding 3 metres in height may arise. The subduction zone encompasses North Halmahera, West Halmahera, Ternate, Tidore Islands and South Halmahera (Kurniawan et al. 2021). Between 1650 and 1999, 32 tsunamis were documented in the Maluku Sea, with approximately four resulting from volcanic eruptions and 28 instigated by seismic activity. The estimated toll of these tsunamis exceeds 7600 lives, with the average interval between seismic tsunamis approximated at 10 years (Hamzah, Puspito & Imamura 2000). The tsunami waves traversing the Maluku Sea will approach coastal regions with reduced wavelengths

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yet significant wave heights. Consequently, coastal areas are at considerable risk of substantial damage from the tsunami.

Based on Indonesian Paleo-Tsunami data, a tsunami event with an observed tsunami wave height of 9 cm occurred on 15 November 2014, in the Jailolo coastal area. Horspool et al. (2013) have predicted the probability of tsunami occurrence in the Indonesian region for 100-, 500- and 2500-year recurrences. For the Jailolo region, the probability of a tsunami hazard exceeding 3 metres in 1 year is approximately 1.2%. For a return period of 100, the estimated tsunami height can reach 3.4 metres, increasing to 12.2 metres for a 500-year return period and 24.6 metres for a 2500-year return period.

The Sendai Framework emphasises that disaster risk reduction action priorities include understanding disaster risks, strengthening disaster risk governance and management, and enhancing disaster preparedness for effective response. Therefore, delineating tsunami hazard zones stands as a paramount element in the realm of disaster risk mitigation. Hazard mapping serves as a tool to illustrate the various dimensions of vulnerability, capacity, exposed populations, assets and the characteristics of hazards and the surrounding environment. This knowledge can be employed for pre-disaster risk assessment, facilitating prevention and mitigation, and guiding the development and implementation of appropriate preparedness and effective responses to disasters (UNDRR 2015).

Several researchers have previously conducted research on mapping the potential hazards and risks of tsunami disasters in the Jailolo area. Amelia et al. (2024) has conducted earthquake and tsunami disaster risk mapping for tourist areas. Furthermore, Ningrum et al. (2021) focused on earthquake risk mapping. Kurniawan et al. (2021) conducted tsunami simulations for disaster mitigation based on earthquake scenarios in the Maluku subduction zone. However, research on tsunami hazard mapping using unmanned aerial vehicle (UAV) technology and tsunami modelling using the numerical simulation method has never been conducted at the research site. This research utilises UAV aerial photography data with data processing using the Structure-from-Motion (SfM) photogrammetry method, GCP (ground central point) and ICP (independent central point) measurements to produce digital elevation models (DEMs) and images that have been tested for geometric accuracy. The advantage of aerial photography using UAVs is that it shows high-resolution topographic data so that tsunami hazards can be mapped clearly and in detail. Aerial photography acquisition using UAV and data processing using the SfM photogrammetry method are relatively easy and inexpensive.

Ultimately, this research aims to map tsunami hazards, identify hazard level zones and analyse the impact of tsunami disasters on populations and buildings in the Jailolo area. Thus, the research will contribute to tsunami disaster risk reduction, improved preparedness and disaster mitigation-based sustainable regional spatial planning. It can also be

used in planning tsunami evacuation routes with a precise, accurate and much more effective model (Marfai et al. 2018).

Research methods and design

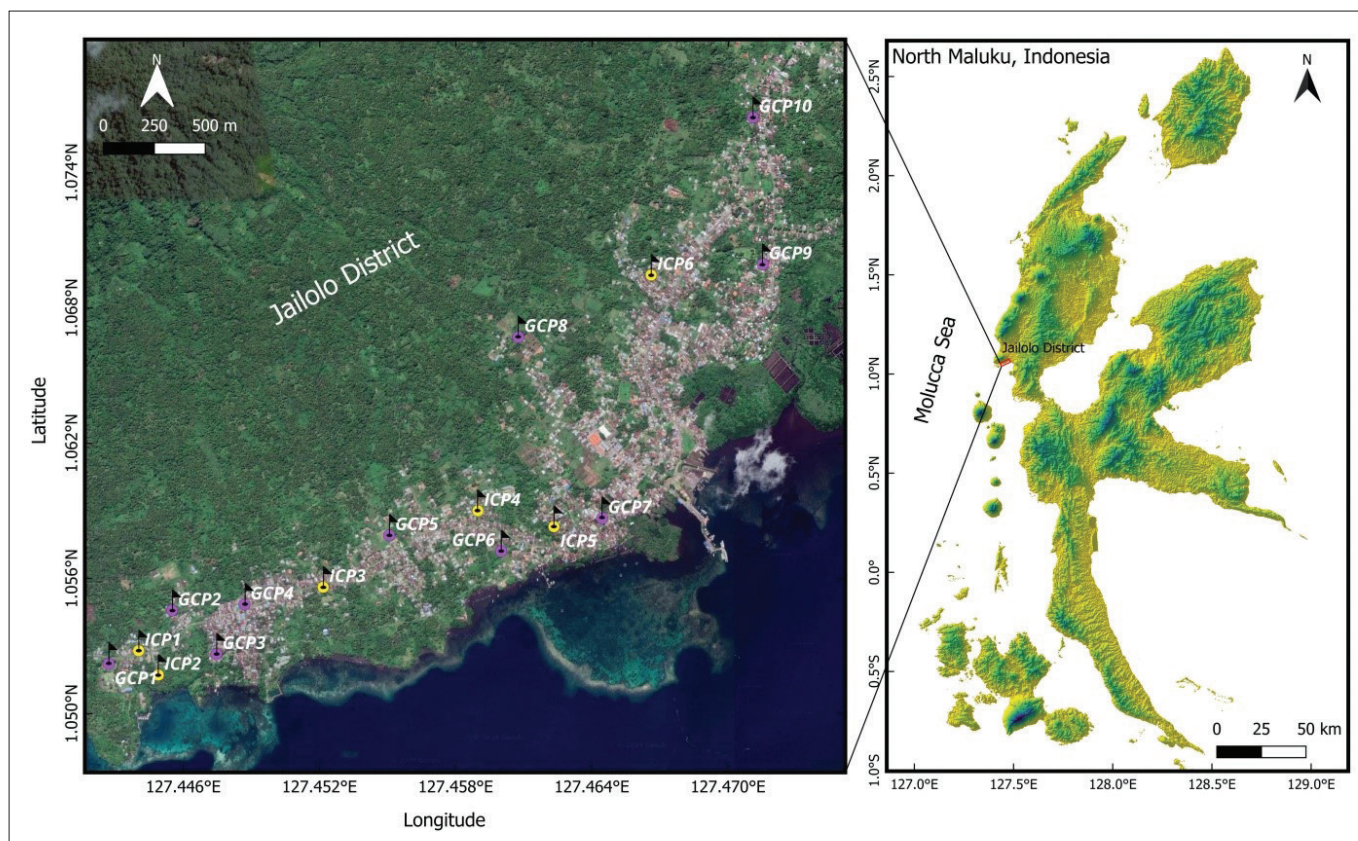
Study area

The research site is located in Jailolo Sub-district, West Halmahera, North Maluku Province, Indonesia (Figure 1). Geomorphologically, the topography of the Jailolo area is about 65% coastal plains and the rest are hills and mountains with altitudes ranging from 7 metres above sea level to 925 metres above sea level (BPS-Statistics Indonesia 2022). The coastal area of Jailolo is dominated by Quaternary volcanic rocks that have undergone weathering and erosion. Quaternary volcanic rocks from past volcanic activities, along with active and inactive volcanoes, also affect the geological composition of the Jailolo region. In addition to volcanic rocks, there are also sedimentary rock formations formed from deposits on the seabed and land. These sedimentary rocks include sandstone, shale and limestone.

Administratively, Jailolo is the capital of West Halmahera District, where most of the government infrastructure, settlements and supporting facilities are built in this area. According to the findings from field investigations, significant infrastructure situated in coastal regions includes government offices, educational institutions, bridges, marketplaces, mosques, churches and residential areas. In addition, the region is experiencing rapid tourism growth and is becoming an economic centre. The coastal area of Jailolo sub-district is directly adjacent to the Maluku Sea, which is the source of tsunami generation in North Maluku, and is in an active subduction zone, making this area very vulnerable to tsunamis and rising sea levels. In addition, the Jailolo area has rivers and valleys that empty into the sea from the mountains, potentially accelerating the spread of tsunamis. Past tsunami hazards, although not very large, remain concerning because of the absence of an efficient and accurate mitigation strategy. This further increases the risk of damage to buildings and population losses. Increasingly densely populated coastal areas make them more vulnerable to tsunami hazards (Marfai et al. 2019; Windupranata et al. 2020). Based on the factors described, this research is highly relevant to the Jailolo coastal area.

Data collection

Input data used in tsunami hazard mapping are fault data from the National Earthquake Center (PUSGEN), bathymetry data (General Bathymetric Chart of the Oceans [GEBCO] and National Bathymetric [BATNAS]), topographic data from the National Digital Elevation Model (DEMNAS), DEM data from the SfM photogrammetry method and land cover data. Fault data are needed for the tsunami-triggering earthquake scenario, including the length, width, strike, dip, rake and dislocation parameter values calculated using the Wells and Coppersmith, Hanks and Kanamori, and Leonard equations. Bathymetry data from GEBCO is a world topographic model for ocean and land that provides elevation data on a grid



Source: Adapted from Google earth, viewed August 2024, from <https://www.google.com/earth>

FIGURE 1: Map of the study area.

with 15-s arc intervals in metres. National Digital Elevation Model topographic data, BATNAS data and land cover data were obtained from the Geospatial Information Agency (BIG). Meanwhile, the UAV topographic data were obtained from the SfM photogrammetry method. The more detailed stages carried out in this research are shown in the form of a flowchart in Figure 2.

Aerial photography data acquisition and processing

Aerial photography data acquisition was conducted in the field using a DJI Mavic Pro 1 UAV with 10 GCP points and 6 ICP points for 3 days at 08:00–12:00 Eastern Indonesia Time, considering light and weather conditions. In order for the GCP points to get high-quality results, it is recommended that at least 10 GCP points are placed evenly and scattered in the area of interest (Agisoft LLC 2020). The coordinates of the GCP and ICP points were measured using an Altus APS3G geodetic Global Navigation Satellite System (GNSS) receiver, which will be tested for spatial data geometry correction or static georeferencing.

The initial preparations made before the acquisition of aerial photography data are to check the weather and wind speed for safe flight, to produce clear and accurate image quality, and to use batteries efficiently. In addition, attention must be given to surrounding objects that can interfere with connectivity between the drone and the remote control, such as Base Transceiver Station (BTS) towers, Extra High Voltage

Transmission Line (SUTET) towers, Wi-Fi signals and steel structure buildings. The mission flight of the UAV vehicle is designed using the Drone Deploy program with an autopilot system flight mode with a mapping flight speed of 6 m/s for an area of interest of ± 500 hectares and an average altitude of 150 metres above the Earth's surface. Shooting aerial photos in the area of interest to get precise and consistent results must follow the requirements for the side overlap and side overlap values of each photo taken. The side overlap and front overlap values used were 60% and 80%, respectively. This mission flight design is carried out to ensure that the aerial photographs obtained can be processed using the SfM photogrammetry method properly. The use of mission flight settings with values below can make the processing results imperfect with high error values and poor accuracy levels.

Processing of aerial photography data from UAVs is assisted by Agisoft Metashape Professional Edition photogrammetry software, which produces DEM data (Groebner 2021). Data representing the contours of the Earth's surface and the features upon it, such as vegetation and structures, is referred to as a digital surface model (DSM). In contrast, data that delineates the surface's form devoid of any objects is known as a digital terrain model (DTM). The final result of SfM data processing in Agisoft Metashape is orthomosaic data in the form of orthoimages generated from the projection of orthorectified aerial photographs onto the surface (Over et al. 2021). The DEMs and orthomosaic data were then exported for further use in data processing for tsunami hazard modelling.

Tsunami inundation modelling

Data processing for modelling potential tsunami hazards uses the numerical simulation method with the help of the computational program Cornell Multi-Grid Coupled Tsunami (COMCOT) model version 1.7. Cornell Multi-Grid Coupled Tsunami simulates the process of tsunami propagation and height (Wang & Power 2011). Cornell Multi-Grid Coupled Tsunami is an algorithm that uses a leapfrog numerical approach to solve shallow water problems. The tsunami hazard modelling simulation in this study describes the flow motion in shallow water by incorporating the friction component of bottom friction (Manning's coefficient) by using the non-linear equation

(Heidarzadeh et al. 2022; Kajiura & Shuto 1990; Santos, Fernandes & Mileu 2022). The basic motion equations and non-linear equations can be expressed as follows in equation 1 (Wang 2009):

$$\begin{aligned} \frac{\partial \eta}{\partial t} + \left\{ \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} \right\} &= -\frac{\partial h}{\partial t} \\ \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left\{ \frac{P^2}{H} \right\} + \frac{\partial}{\partial x} \left\{ \frac{PQ}{H} \right\} + gH \frac{\partial \eta}{\partial x} + F_x &= 0 \\ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left\{ \frac{PQ}{H} \right\} + \frac{\partial}{\partial y} \left\{ \frac{Q^2}{H} \right\} + gH \frac{\partial \eta}{\partial y} + F_y &= 0 \end{aligned} \quad [\text{Eqn 1}]$$

$$F_x = \frac{gn^2}{H^{7/3}} P (P^2 + Q^2)^{\frac{1}{2}}$$

$$F_y = \frac{gn^2}{H^{7/3}} Q (P^2 + Q^2)^{\frac{1}{2}}$$

For wave motion, especially in the open sea, the variables used in the equations include water surface conditions (η), volume fluxes in the x and y directions (P , Q), the longitude and latitude positions of waves (x , y), the Earth's radius, gravitational acceleration (g), total water depth (H) and the Coriolis force coefficient because of Earth's rotation. In non-linear wave motion, the Coriolis force is replaced by bottom friction in the x and y directions (F_x , F_y), which is calculated using the Manning coefficient (n) to account for surface roughness based on bathymetry and land cover. This substitution adjusts the non-linear settings to better predict wave motion towards and along coastal areas.

Mathematically, total water depth is represented as $H = h + \eta$, while flux volumes in the x and y directions are measured in m^2/s . Bottom friction (F_x , F_y), is determined by the Manning coefficient, which is interpreted based on bathymetric characteristics and land cover classifications (Wang 2009). In this study, land cover classifications were derived from aerial photographs and correlated with 2019 land cover data from the Ministry of Environment and Forestry of the Republic of Indonesia (Table 1).

Input data for the COMCOT computational program are fault data in the form of length, width, strike, dip, rake and dislocation values. Based on the scenario of an

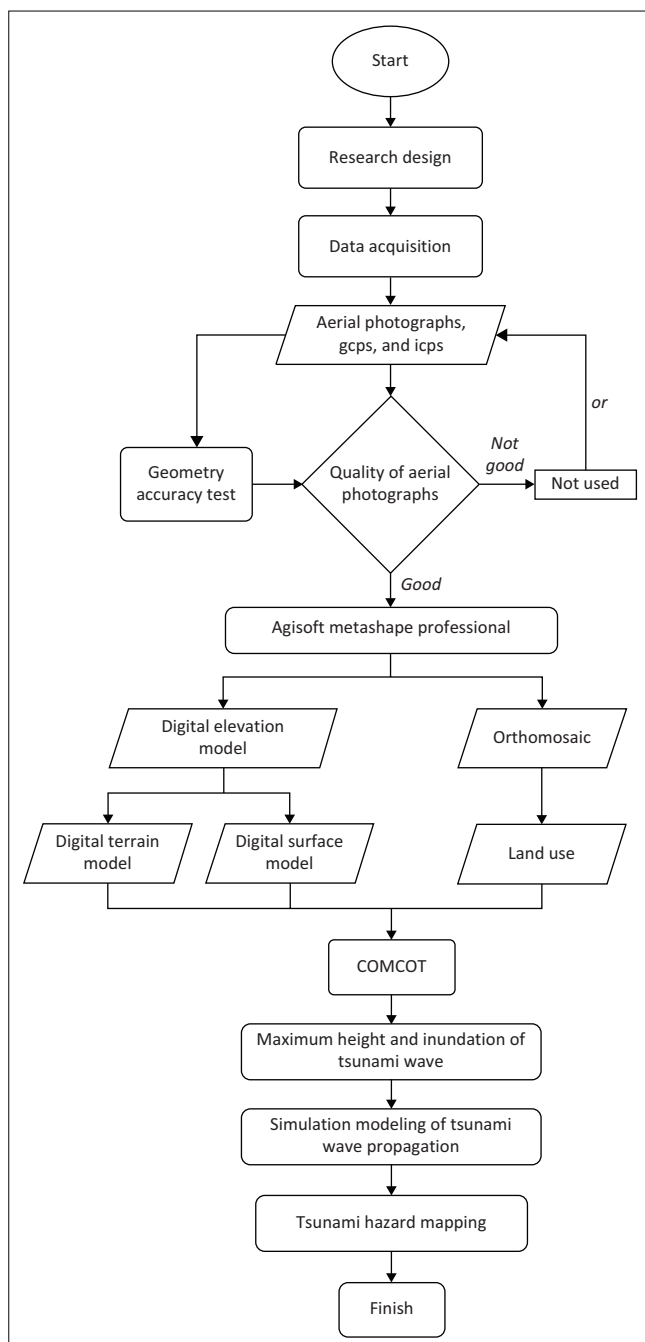


FIGURE 2: Research flowchart.

TABLE 1: Manning's coefficient values for various land types.

Land use type	Manning coefficient (n)
Water bodies (rivers, lakes, swamps)	0.007
Forests, jungles (trees, forest)	0.070
Built-up areas (residential areas)	0.035
City centre	0.100
Mudflats, ice, open fields without crops (default areas)	0.015
Woodland (farmland, mangrove)	0.025
Ponds	0.010
All terrains (shrubs or bushes)	0.040

Source: Berryman, K., 2006, *Review of tsunami hazard and risk in New Zealand*, p. 139, Institute of Geological and Nuclear Sciences, Lower Hutt; and, Wang, X. & Power, W.L., 2011, *COMCOT: A tsunami generation propagation and run-up model*, GNS Science Report, GNS Science Lower Hutt

earthquake in the Maluku Sea with a magnitude of Mw 8.2 from the data of the National Earthquake Center (PUSGEN 2017), the tsunami-generating fault parameters used were calculated using the equation from Wells and Coppersmith (1994).

In the tsunami hazard modelling, four layers (Figure 3) were used: the first layer used GEBCO bathymetry data, the second layer used BATNAS data, the third layer used DEMNAS data and the fourth layer used DTM data from UAV and DEMNAS. The tsunami simulation results, obtained by overlaying DTM-UAV data with the SfM photogrammetry method, provided high-resolution topographic data. Unmanned aerial vehicles can map coastal areas and help plan tsunami evacuation routes by taking high-quality aerial photographs (Marfai, Fatchurohman & Cahyadi 2019).

The numerical data processing results illustrate tsunami simulation models, including tsunami wave height, wave arrival time and inundation distance. These results were overlaid with DEM and orthomosaic data to accurately identify the impacts. This analysis was then used to develop a tsunami hazard map with various hazard levels based on Indonesian National Agency for Disaster Countermeasure (BNPB 2012). The tsunami hazard maps clearly delineate the affected areas and served as a reference for government policy in mitigation and evacuation planning.

Ethical considerations

This article followed all ethical standards for research without direct contact with human or animal subjects. However, we emphasise that flight safety standards during the aerial photography data acquisition process are strictly followed by the appropriate permissions from the government and local stakeholders at the research site to ensure safety and minimal disruption to the local environment and community.

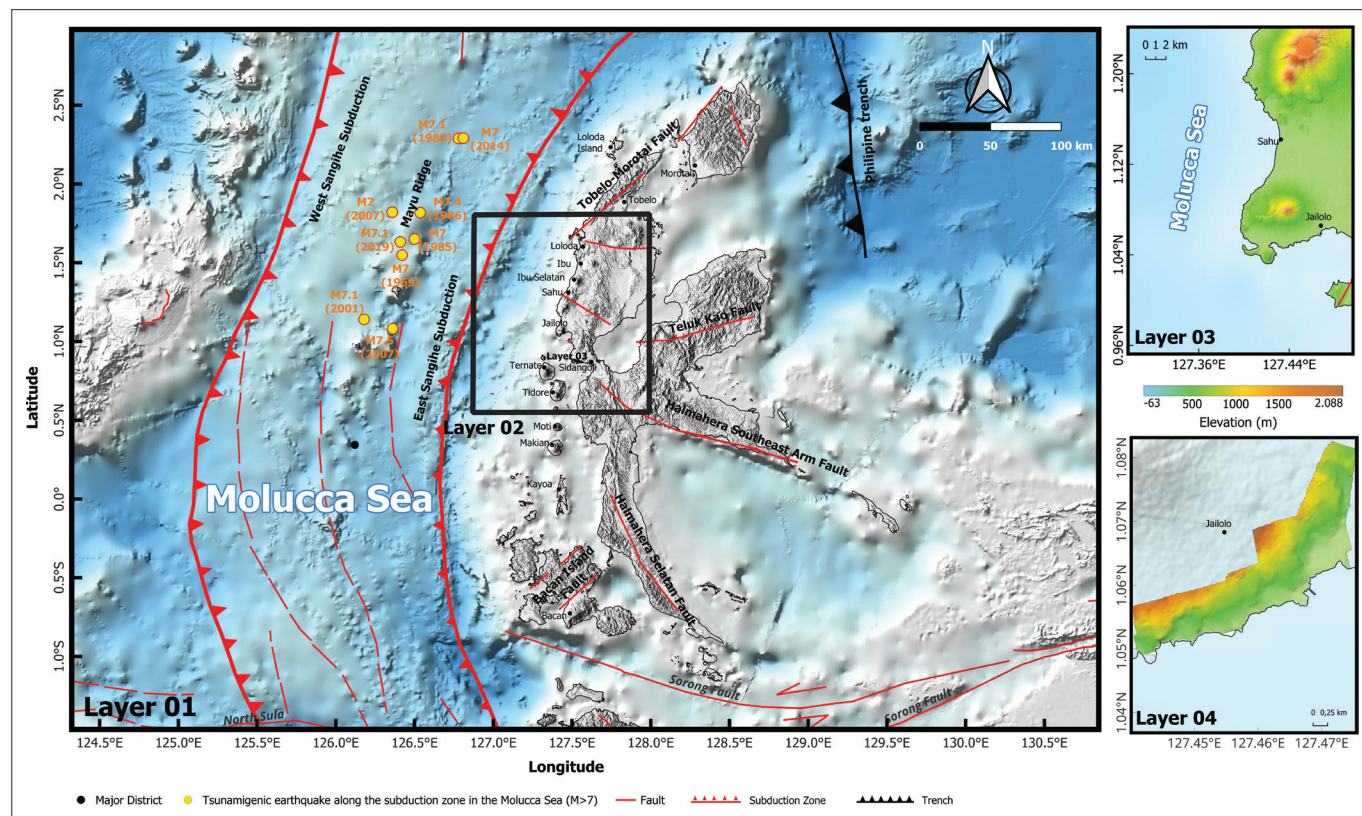
Results

Results of structure-from-motion-unmanned aerial vehicle photogrammetry

Aerial photo data processed with the SfM photogrammetry technique in the Jailolo coastal area obtained 2849 photos that were used for further data processing. Furthermore, the horizontal and vertical accuracy of aerial photography results can be known by conducting geometry accuracy tests. The results of this test were used to create DEM (DTM and DSM) maps as shown in Figure 4. Independent central point points were used for geometry accuracy tests and to produce Root Mean Square Error (RMSE) values that were used as validation of the spatial accuracy of aerial photographs. The horizontal RMSE value obtained is 0.0 metres and the horizontal RMSE is 0.3 metres.

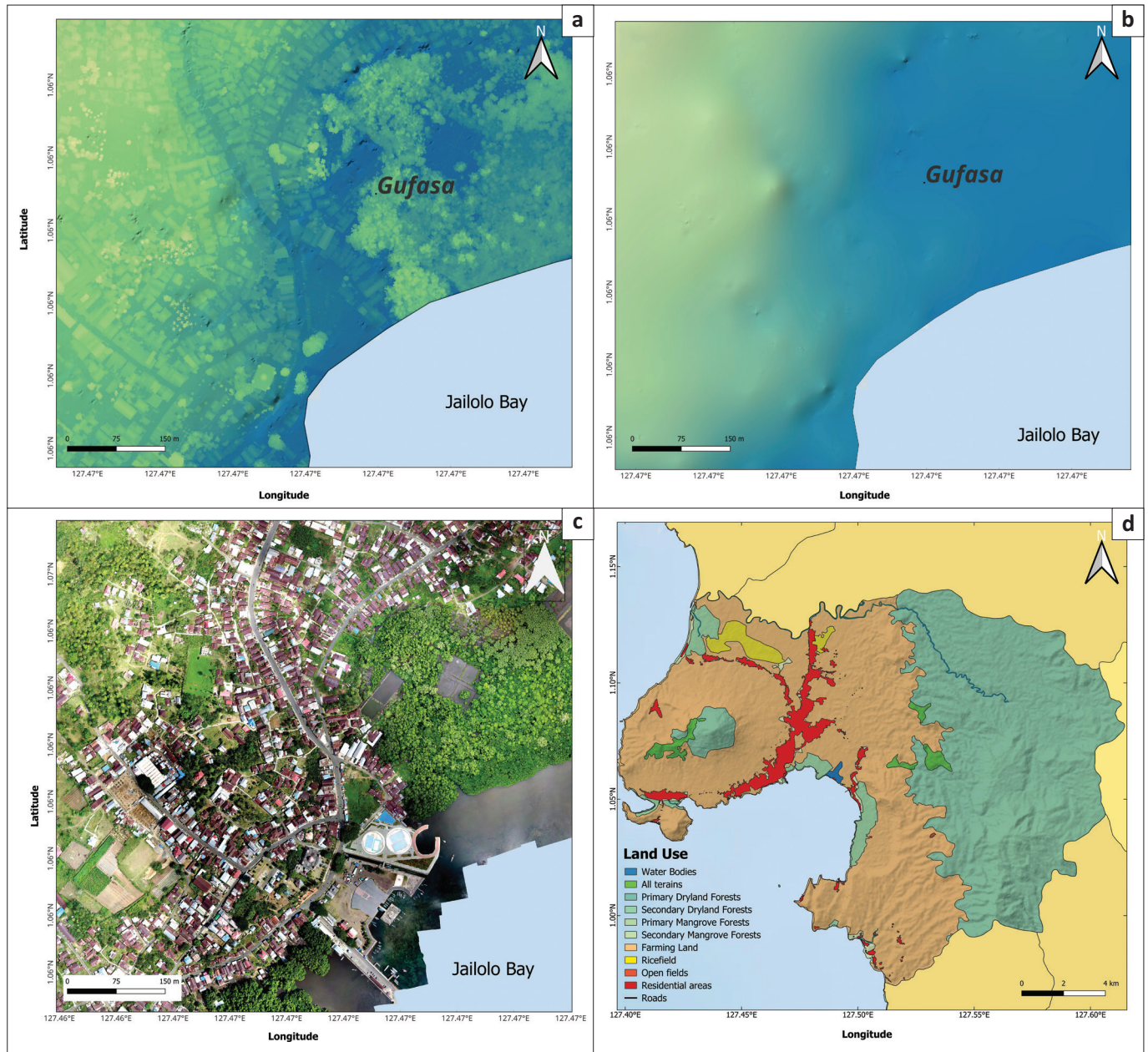
Cornell Multi-Grid Coupled Tsunami modelling

The numerical simulation method was utilised to model potential tsunami hazard using the computational program COMCOT version 1.7. Cornell Multi-Grid



Source: Adapted from General Bathymetric Chart of the Oceans (GEBCO), 2023, *Global gridded bathymetric data sets*, viewed August 2024, from <https://www.gebco.net/>

FIGURE 3: Four layers used for data processing in Cornell Multi-Grid Coupled Tsunami, with layer 4 representing the research location.



Source: Ministry of Environment and Forestry of Indonesia, 2019, *Shapefile Peta Tutupan Lahan KLHK Terbaru Seluruh Indonesia*, viewed 20 March 2023, from <https://www.lapagis.com/2019/05/shapefile-peta-tutupan-lahan-klhk-2017.html>

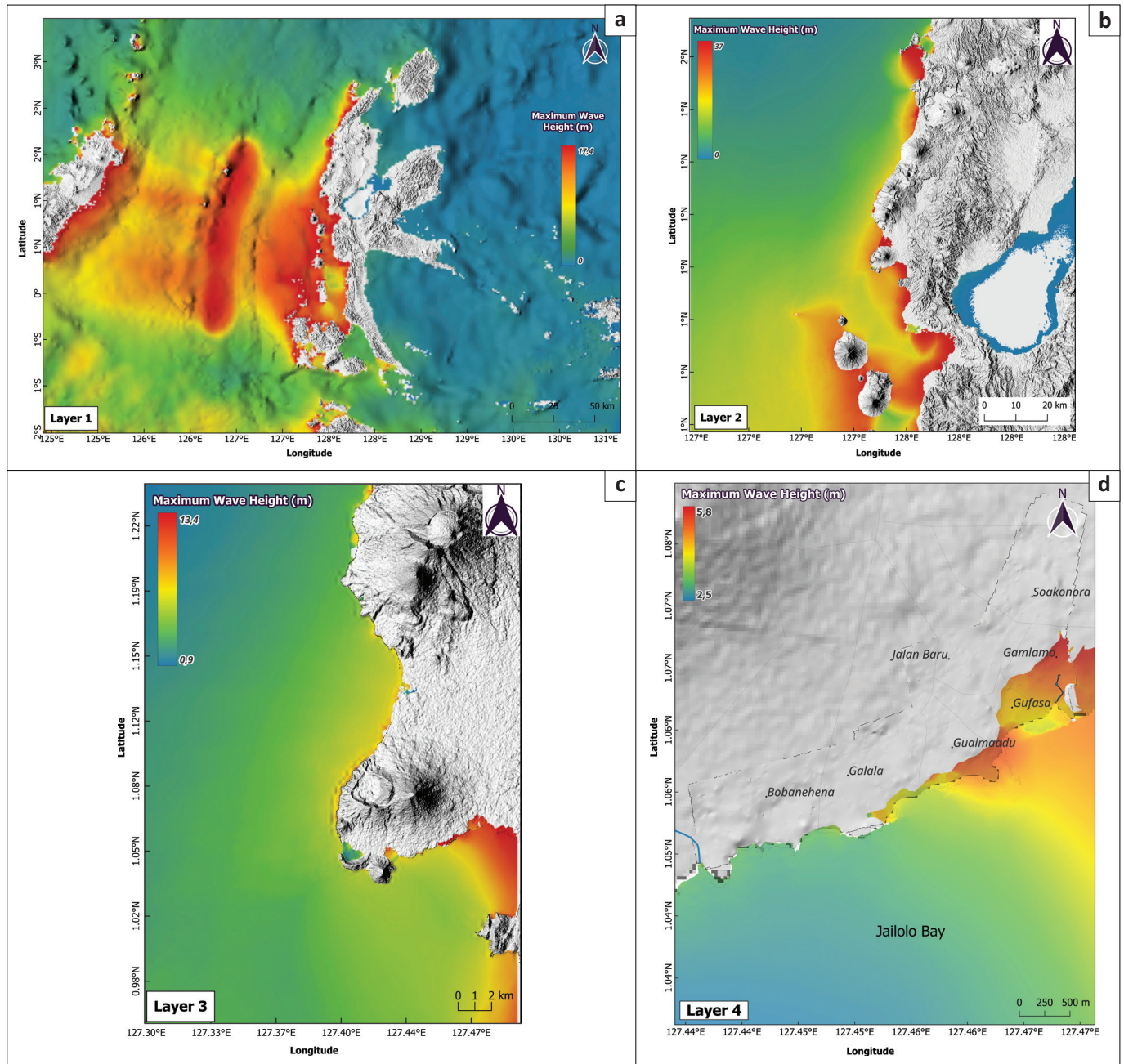
FIGURE 4: Aerial photography map results: (a) digital terrain model, (b) digital surface model, (c) orthomosaic of a coastal village in Jailolo and (d) spatial variation of Manning's roughness, represented by different colour scales for different land uses, obtained from aerial photo digitisation and the Ministry of Environment and Forestry of Indonesia (2019).

Coupled Tsunami simulates tsunami propagation and wave height (Wang & Power 2011). This calculation employs the spatial variation of Manning's roughness coefficient, represented through land cover classification. The land cover classification was derived from the digitisation of aerial photographs and correlated with land cover data from the Ministry of Environment and Forestry of Indonesia in 2019 (Figure 4d).

The numerical data processing results illustrate the tsunami simulation model, showing the maximum tsunami wave height values for each layer used and the extent of tsunami inundation. These results were then overlaid with DEMs and orthomosaic data to clearly and accurately identify the

potential impacts. The coastal area of Jailolo, which directly borders the Maluku Sea, has a high tsunami risk, as indicated by the tsunami wave propagation simulation, with wave heights ranging from 5.8 to 17.4 metres. The maximum tsunami wave heights recorded were 17.4 metres in Layer 1, 37 metres in Layer 2, 13.4 metres in Layer 3 and 5.8 metres in Layer 4 (Figure 5).

The maximum tsunami wave height map can be further analysed to develop tsunami hazard maps with various hazard levels. These maps clearly indicate the areas affected by tsunamis and serve as a reference for government policies on mitigation and evacuation planning, as shown in Figure 6.



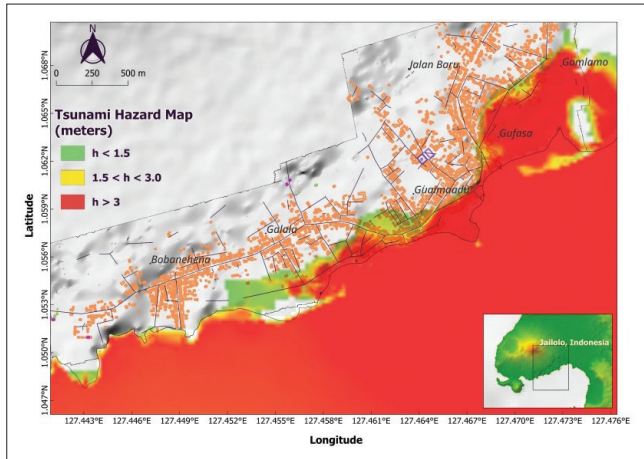
Source: Adapted from General Bathymetric Chart of the Oceans (GEBCO), 2023, *Global gridded bathymetric data sets*, viewed August 2024, from <https://www.gebco.net/>

FIGURE 5: Simulation of tsunami wave propagation based on an M8.2 earthquake at: (a) Layer 1, (b) Layer 2, (c) Layer 3 and (d) Layer 4.

The tsunami hazard mapping derived from the Numerical Simulation-COMCOT modelling results was then classified based on the maximum tsunami wave height in the Jailolo coastal area. The tsunami hazard classification is divided into three categories: low hazard ($h_{\max} < 1$ m), medium hazard ($1 \text{ m} < h_{\max} < 3$ m) and high hazard ($h_{\max} > 3$). The tsunami inundation extended approximately 700 metres inland from the shoreline, covering an area of ± 119.31 hectares. In addition to urban settlements that were inundated, the affected areas based on land cover included agricultural land, primary mangrove forest and secondary mangrove forest. High-hazard zones encompass settlements, agricultural land and mangrove forests in the villages of Gamlamo, Gufasa, Guaemaadu, Galala and Bobanehena.

Discussion

This study found that the coastal area of Jailolo is highly vulnerable to tsunamis. With inundation heights exceeding 3 metres, various infrastructures will be affected, making the region highly susceptible to tsunami-induced damage. This tsunami threat is because of the fact that the study area is located in a seismically active zone on the Pacific ring of fire. This is influenced by the convergence of several macro and micro plates, such as the Eurasian Plate, Australian Plate, Pacific Plate, Philippine Sea Plate, Sangihe Plate, Maluku Sea and Halmahera Plate (Bock 2003; Hall et al. 1988; Hall & Wilson 2000; Lallemand et al. 1998; Moore & Silver 1982; Silver & Moore 1978; Watkinson & Hall 2017). The plate convergence movements around Halmahera, the Banda Arc,

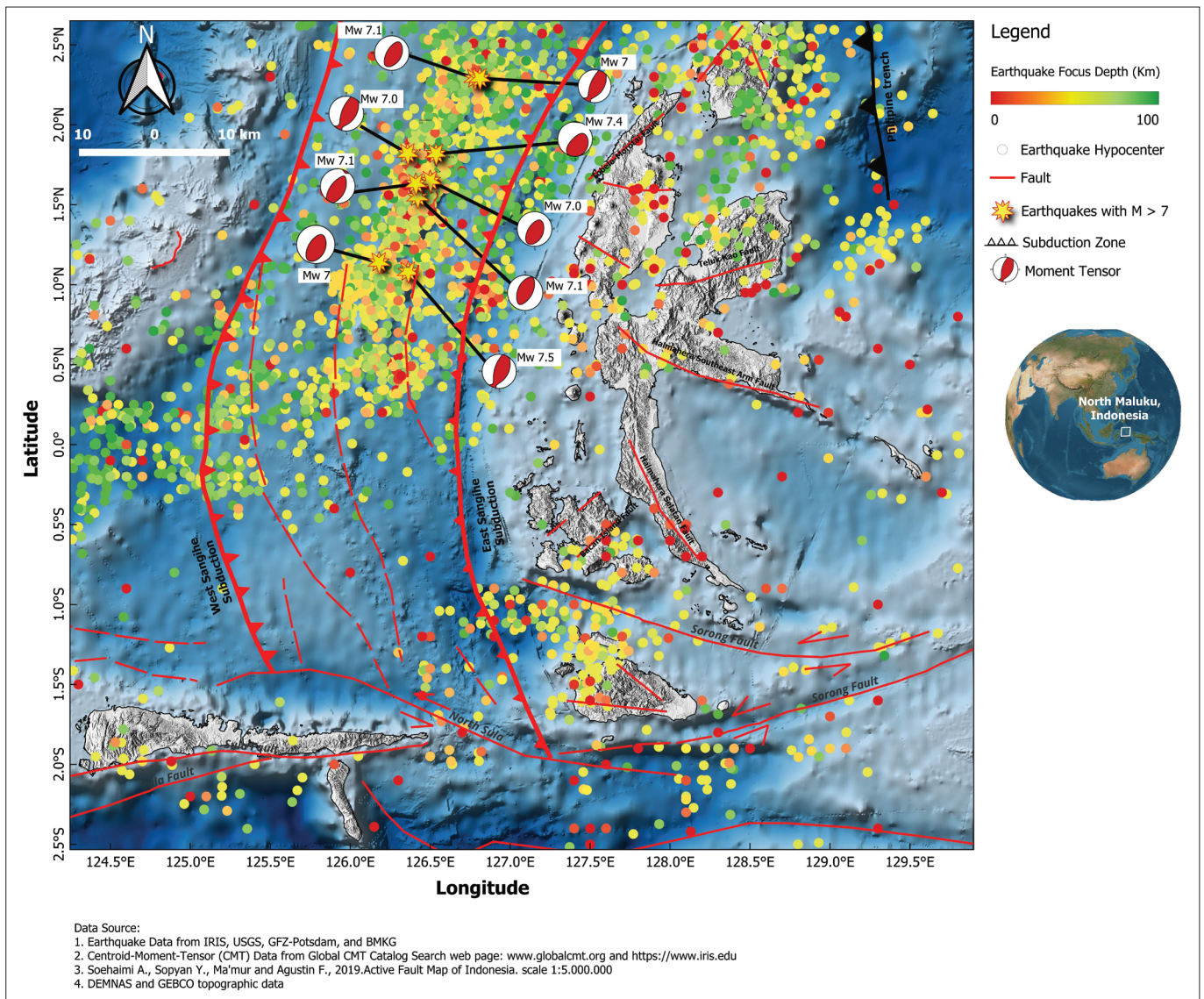


Source: Adapted from General Bathymetric Chart of the Oceans (GEBCO), 2023, *Global gridded bathymetric data sets*, viewed August 2024, from <https://www.gebco.net/>

FIGURE 6: Tsunami hazard map derived from tsunami modelling, overlaid with digital elevation model from aerial photography and National Digital Elevation Model.

northern Papua and northern Sulawesi create an active subduction zone. Beneath the two active volcanic arcs of Sangihe and Halmahera is an active plate collision arc that forms the Maluku Sea (Cardwell, Isacks & Karig 1980; Hall 1987; Hamilton 1979; Hatherton & Dickinson 1969; Silver & Moore 1978). The microplate, which is part of the macroplate that moves and is trapped between the converging plates, frequently causes earthquakes in the Maluku Sea (Figure 7), making it a source of tsunami generation (Lessy & Sabar 2021).

The utilisation of UAV technology with the SfM photogrammetry technique represents an innovative approach to producing high-resolution aerial photographs (Khan, Gupta & Gupta 2020). Unmanned aerial vehicles and SfM photogrammetry offer significant advantages in accuracy because of their ability to capture aerial images in the visible light spectrum, which provides highly



Source: Adapted from General Bathymetric Chart of the Oceans (GEBCO), 2023, *Global gridded bathymetric data sets*, viewed August 2024, from <https://www.gebco.net/>

FIGURE 7: Seismic map and faults in the Maluku Sea Subduction Zone with potential for tsunami generation.

detailed spatial resolution. These aerial photographs can then be used to generate DEMs, which are integrated into tsunami modelling using numerical modelling methods. Photogrammetric methods produce DEMs with significantly better spatial resolution than those generated from satellite remote sensing imagery, such as DEMNAS (8 m) and SRTM (30 m). The accuracy of this method is further enhanced by incorporating geodetic GPS, which improves DEM processing precision.

Geometric accuracy tests are used to determine the precision of coordinates from aerial photographs both vertically and horizontally, serving as standards for base map accuracy. Vertical accuracy is measured using LE90 (linear error 90%), while horizontal accuracy is assessed using CE90 (circular error 90%). The results of aerial photography yielded an LE90 vertical accuracy of 0.15 metres for DEM data and a CE90 horizontal accuracy of 0.5 metres for orthomosaic maps. This accuracy test complies with the standards set by the Geospatial Information Agency Regulation Number 18 of 2021 for mapping scales of 1:1000 for LE90 and 1:5000 for CE90. These findings indicate that the DEMs (DTM and DSM) and orthomosaic maps produced in this study meet high-scale accuracy requirements and are suitable for tsunami disaster mapping.

The numerical simulation method, utilising the COMCOT computing program, facilitates the examination of tsunami propagation processes and wave height at the study site, thereby enhancing the understanding of tsunami impacts. As noted by Al'ala et al. (2016), the COMCOT application enables the modelling of tsunami run-up by simulating the propagation of tsunami waves originating from the fault area, yielding results that closely align with actual observations. This modelling incorporates Manning's roughness coefficient data derived from land cover classification to analyse its effects on inundated areas.

Conclusion

This study highlights the vulnerability of North Maluku, particularly Jailolo, to tsunamis. The tsunami run-up and its impact depend significantly on the specific characteristics of the affected region. The numerical simulation results indicate that tsunami inundation in the coastal area of Jailolo can extend up to approximately 700 metres inland, emphasising the need for comprehensive disaster preparedness and mitigation strategies.

Several challenges were encountered during this study. The use of UAVs for high-resolution aerial mapping, while beneficial, posed limitations because of their restricted battery capacity, requiring multiple flights and extended data collection time compared to satellite imagery. Additionally, UAVs cover smaller areas per capture, necessitating more flights for extensive mapping. The processing of UAV-derived imagery was also computationally demanding because of the high spatial resolution, requiring substantial processing power and extended computation time. These factors highlight the need to align UAV photogrammetric applications with study objectives to optimise efficiency.

This study is also subject to certain limitations. One key limitation is the modelling of the earthquake source fault parameters, which influences tsunami generation and propagation. A more detailed and precise fault model would enhance the accuracy of tsunami run-up predictions. Future studies should incorporate refined seismic source models to establish a stronger correlation between earthquake magnitude and tsunami impact.

Despite these limitations, the findings of this study have significant implications for disaster risk management. The development of tsunami hazard maps provides critical information for policymakers, urban planners and emergency responders. These maps serve as essential tools for spatial planning, evacuation route design and community preparedness initiatives.

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Competing interests

The authors declare that they received funding from the Ministry of Education, Culture, Science and Technology of the Republic of Indonesia which may be affected by the research reported in the enclosed publication. The author has disclosed those interests fully and has implemented an approved plan for managing any potential conflicts arising from their involvement. The terms of these funding arrangements have been reviewed and approved by the affiliated University in accordance with its policy on objectivity in research.

Authors' contributions

R.W.N. contributed to conceptualisation methodology and writing. W.S. contributed to the conceptualisation, formal analysis, software and validation. W.W., S.S. and M.R.L. assisted with supervision. D.O. contributed to the software. M.S. contributed to the software and data collection. W.R. contributed to the visualisation. M.A. and R.N.A. contributed to the investigation and data curation.

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Data availability

The data that support the findings of this study are available on reasonable request from the corresponding author, R.W.N.

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