Estimated Tsunami Arrival Times for the Ambon Bay Area, Indonesia: Linking Tsunami Hazards Information to the City's Evacuation Readiness

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Abstract

The Ambon Bay Area, with the current population of around 350,000 in Ambon City located along the Bay, has a central function from the perspectives of geography and economic activities in Eastern Indonesia, but also the Bay is surrounded by a number of tectonic and non-tectonic tsunami sources, with insufficient information that could be integrated into a city-wide evacuation procedure for Ambon City. This study is aimed at estimating tsunami arrival times based on deterministic tsunami modeling, assessing tsunami evacuation readiness of the communities and inland facilities for city-wide evacuation. Two main methods are applied in this research, first by simulating a numerically deterministic model of a tsunami, and second by assessing the community's perceptions on their readiness to evacuate should any tsunami happen. Tsunami simulations were performed using the Cornell Multi-Grid Coupled Tsunami Model (COMCOT). Bathymetry data were taken from GEBCO and Admiralty charts published by PUSHIDROSAL (Hydro-Oceanographic Center, Indonesian Navy). The simulations took four historical tsunamis sources, namely from Tanimbar trough (two events), Weber Sea, and from Banda Detachment. The results show that the shortest arrival time was around 37 minutes and it was indicated at the eastern part of the bay. Meanwhile, at some major populated areas around the bay, the shortest arrival times were between 42 and 56 minutes. However, tsunami evacuation routes in the city have not been fully identified. Only one siren tower is available and it is not enough to reach the whole city area, and only around 20% of the research respondents have participated in tsunami evacuation drills. Most of the respondents were obtained for the tsunami awareness information from places of worship. Essentially, concerns are over the absence of emergency traffic management facilities and insufficient tsunami early warning facilities (such as sirens).

Introduction

Tsunamis in recent decades have been regarded as one of the deadliest disasters in Indonesia, which has been hit by many tsunami events that killed more than 100,000 individuals (Sieh 2005; Papadopoulos et al. 2006), but to date there is no comprehensive understanding of the characteristics of tsunamis (KURITA et al. 2007). Every tsunami event results in new phenomena and new understandings of tsunamis. For example, the 2004 Indian Ocean tsunami shocked most disaster researchers concerning the potential disaster from a giant tsunami in the eastern basin of the Indian Ocean. The last two tsunami events, namely the 2018 Palu tsunami and the 2018 Mount Anak Krakatau tsunami (Indonesia), also created many theories on the impacts of tsunamis along coastal areas, and the way to understand the characteristics of tsunamis (Giachetti et al. 2012; Heidarzadeh et al. 2019a; Heidarzadeh et al. 2019b; Paris et al. 2020). The 2018 Palu tsunami occurred inside a long bay and it was caused by submarine landslide (Pakoksung et al. 2019). Extremely short arrival times left the coastal communities around the bay with a limited time window to evacuate (Syamsidik et al. 2020). This tsunami caused more than 400 deaths, as well as other cascading events around the same time of this event. Therefore, our understanding toward the characteristics of tsunami around a bay should be strengthened and developed further. A bay is often regarded as a safe location from impacts of extreme waves or weather, but this is not always the case, and this fact can lead to a mistaken understanding of a bay's function in protecting areas within it from tsunamis. Therefore, researching the potential impacts of tsunamis in a bay area is essential. Further, assessing the bay community's tsunami awareness would provide a more comprehensive way to increase the area's readiness for the disaster.

Ambon City is situated inside the Ambon Bay Area, similarly to the condition of Palu Bay, despite the geographical context, to the knowledge of the present authors there has been no research reporting on the impacts of any tsunami within the Ambon Bay Area. Further, it is noteworthy that Eastern parts of Indonesia receive less attention despite its tectonic complexities and multiple tsunami events in the past (Løvholt et al. 2012; Pranantyo dan Cummins 2020). This might be parallel to the economic growth and development whereby the geographical and cultural differences divide eastern and western Indonesia. In the last century, there were a number of tsunamis around the Maluku islands of eastern Indonesian. Among the ways to strengthen the awareness of a coastal city to tsunamis, there is the provision of information related to tsunami estimated arrival times and the area of tsunami inundation (Muhari et al. 2012; Takagi et al. 2019; Jihad et al. 2021; Jihad et al. 2023). The connection between the number of casualties and tsunami arrival time could have an inverse correlation, as was found in the case of Sendai plain during the 2011 Great East Japan Earthquake and Tsunami (GEJET) (Latcharote et al. 2018). Tsunami arrival times within a bay area could be significantly influenced by the hydrodynamic condition of the tsunami in the bay, as in the case of the Palu 2018 tsunami (Husrin et al. 2020). By knowing tsunami arrival times, disaster managers and city planners could then set out a plan for tsunami evacuation in the city. It can be a good basis for determining evacuation routes, safe points, and also for designing tsunami evacuation buildings. Estimated tsunami arrival time (ETA) can be based on the crest-trough of the leading locked waves can present good results, as in the case of Hunga Tonga-Hunga Ha'apai 2022 tsunami (Ren et al. 2023) in the western South Pacific Ocean.

The tsunami arrival times could also be connected to a community's readiness in order to determine if the hazards information could be utilized by the readiness of the community at risk (Paton et al. 2008). They could also be aligned to the willingness of the community to respond to any incoming hazards with their provided capacities and facilities existing in the community. Therefore, coupling the ETA and the community readiness is essential to assess if both sides of the tsunami disaster could be connected properly. However, both sides of the tsunami information i.e. ETA and community's readiness for Ambon Bay Area are not yet available.

This study is aimed at coupling both ETA and tsunami readiness information for the Ambon Bay Area to increase tsunami awareness at this location. We employed a deterministic model of tsunami hazards based on a series of tsunamis that occurred in the past and struck the Ambon Bay Area. This article is expected to fill the gaps on tsunami research for eastern Indonesia and to promote ways to perceive tsunami readiness for a bay area.

Study Area

Geographical Context

Ambon City has a mid-sized population (around 300,000 people in 2022) and is situated along the Ambon Bay Area. Most of the population reside on the south bank of the bay. Meanwhile, on the north bank of the bay, there are a number of important facilities such as Universitas Pattimura (the largest state university in Maluku), Pattimura Airport, a Naval Base, and a provincial hospital. Figure 1 shows Ambon City at the Ambon Bay Area and the epicenters of past earthquakes that triggered tsunamis.

Ambon Bay Area is 33 km in length with a morphology that is like an acute trapezoid, and the bay mouth is 8.5 km wide. The bay is divided into two parts, namely outer bay and inner bay and the two parts are divided by a narrow strait that is connected by the famous Merah Putih bridge. The outer bay has a deeper bathymetry than the inner bay. At the outer bay depths can reach up to 600 m at the middle of the bay. This is why the bay has a strategic position with multi-purpose functions, including the Naval Base.

The city is divided into five sub-districts of *kecamatan* (Indonesian language), and four of them are situated within the Ambon bay, namely *Kecamatan* Teluk Ambon, Baguala, Sirimau and Nusaniwe. Meanwhile, the Kecamatan South Leitimur faces a the south-east direction towards Banda Sea. Most of the population of the city reside in Kecamatan Sirimau and Baguala. Unlike other sub-districts, Kecamatan Baguala is situated in a low-lying area. This is why after the 2019 earthquake, the central business district (CBD) of the city was moved to Baguala. A village name Passo in Baguala has both ends of its area connected to the sea. The other sub-districts have a steep-slope topography. At the southern bay side, a flat area could only be identified around 500 km from its coastline. A similar condition was found at the northern part of the bay. This could benefit the provision of fast tsunami evacuation routes as higher ground could immediately be reached within 0.5- 1.0 km from the coastline.

Tsunami Contexts

A number of tsunamis have been reported to take place around Maluku Province based on several sources. Figure 2 shows the epicenters of tectonogenic tsunami since 1800. There are at least 13 events of tsunamis around the Maluku Islands with varying magnitudes or impacts and different levels of validity.

Table 1
List of tsunami events around the Maluku Islands of Indonesia (Setiyono et al. 2019).

No.	Date of the event	Magnitude (Mw)	Long. Lat.	Depth (km)	Impacts	Ref.
1.	June 16, 2021	5.8	129.50 -3.59	10	Tsunami was observed on the southern coast of the Seram Island	USGS
2.	January 28, 2004	6.8	127.44 -3.01	33	Observed around Namlea	USGS and BMG
3.	March 12, 1983	5.8	127.89 -4.04	33	Light damage around Ambon City	E.I
4.	January 15, 1975	5.9	130.0 -5.00	-	Severe damages in Bandanaira -81 houses major damages, 4 houses moderate damages, 2 houses minor damages	E.R
5.	March 5, 1975	6.5	126.1 -2.4	-	1.2 m of tsunami depth was observed around Sanana of Maluku.	E.R
6.	January 25, 1965	6.3	126.1 -2.6	33	Five people dead at Sanana of Maluku	S.I
7.	October 8, 1950	7.6	128.3 -3.8	-	The strong wave destroyed the houses in Hutumuri villages	USGS
8.	February 2, 1938	8.5	131.5 -5.0	33	Major damages were observed in Banda Island and Kei Islands	GN-2
9.	September 25, 1859	6.8	130.5 -5.5	-	There was very strong shock on the islands of Lonthor and Neira	USGS
10.	November 26, 1852	-	-	-	Some houses collapsed due to the tsunami on Banda Neira Island and Banda Islands	NT
11.	December 16, 1841	-	-	-	Some ships were damaged at Galaga bay and on Buru Island	NT
12.	September 12, 1763	-	130 -6	-	There was a strong earthquake, lasting 4 minutes, on the Banda Islands	USGS
13.	February 17, 1674	6.8	127.75 -3.75	40	An extreme earthquake with a tsunami just on the north coast of Hitu (100 m).	USGS,and (Pakoksung et al. 2023)

Note: Ref. (References), USGS = United States Geological Survey, BMG = BMKG = Meteorological, Climate, and Geophysical Agencies of Indonesia, E.I.=Earthquake Indonesia, E.R.= Macro Seismic Survey Report, NT.= Natuurkundig Tijdschrift foor Nederlandsch-Indiea (Physics Journal for the Dutch East Indies), GN = Geophysical Note, and SI.= Seismology in Indonesia.

No.	Date of the event	Magnitude (Mw)	Long. Lat.	Depth (km)	Impacts	Ref.
14.	August 1, 1629	9.2	130.5 -7.27	20		(Liu and Harris 2014)
15.	1852	8.4	132.32 -6.20	20		(Cummins et al. 2020)
16	1852	8.4	131.69 -4.81	10	Tsunami was observed around Saparua Island in the province of Maluku	(Cummins et al. 2020)
17	1629					
Note: Ref. (References), USGS = United States Geological Survey, BMG = BMKG = Meteorological, Climate, and Geophysical Agencies of Indonesia, E.I.=Earthquake Indonesia, E.R.= Macro Seismic Survey Report, NT.= Natuurkundig Tijdschrift foor Nederlandsch-Indiea (Physics Journal for the Dutch East Indies), GN = Geophysical Note, and SI.= Seismology in Indonesia.						

Methods

This research applies two steps. First, a series of numerical simulations were performed. This was to investigate tsunami ETA at selected locations with the Ambon Bay Area and map the maximum tsunami inundation based on a series of tsunami sources. Second, the research was performed to assess the community's readiness to evacuate should any tsunami occur inside the Ambon Bay Area.

Numerical Simulations

Numerical simulations were performed using Cornell Multi-Grid Coupled Tsunami Model (COMCOT). The COMCOT applies Shallow Water Equations (SWEs) with two modes, i.e. linear and nonlinear SWEs. Both modes of equations were used in this research. Linear SWEs were adopted for offshore layers. Meanwhile, nonlinear SWEs were applied at the innermost layer of the simulations. These actions make the computational process more efficient and the nonlinear SWEs is better when presenting effects of nonlinear process of tsunami wave propagation around the nearshore area. The SWEs were solved using the leap-frog based finite difference method. The linear SWEs can be seen in Equations (1) to (3).

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\phi}\left\{\frac{\partial P}{\partial \phi} + \frac{\partial}{\partial \phi}(\cos\phi Q)\right\} = 0 \ (1)$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R\cos\phi}\frac{\partial \eta}{\partial \psi} - fQ = 0, (2)$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial \eta}{\partial \phi} + fP = 0, (3)$$

where η is water level fluctuation (m), t is time (s), and *h* is the tsunami flow depth in land area (m). The notations of P and *Q* represent water volume fluxes for x- (east-west) and y- (north-south) directions, respectively. Here, *P* was calculated as *hu* and Q the product of *hv. u* and *v* represent depth-average velocity in at x- and y-directions, respectively. In Layers 1 to 3, this research adopts the spherical coordinate system as the impacts of Coriolis Force (*f*) are significant. Further, *R* is for the radius of the earth. Components f, Fx,y, and H are given in Equations (4) to (7).

$$f = 2\Omega \sin\phi$$

4

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$$F_x = \frac{gn^2}{H^{7/3}} P\left(P^2 + Q^2\right)^{1/2}, (5)$$

$$F_y = \frac{gn^2}{H^{7/3}} Q\left(P^2 + Q^2\right)^{1/2}, (6)$$

$$H = \eta + h, (7)$$

here *H* is total depth at the sea grids (m). As the h is zero at the tsunami runup area, the H will be equal to the tsunami flow depth at the area. Furthermore, Ω is for the rotation of the earth. The earth gravitational acceleration is represented by g. Landuse type at the simulation domains can influence the hydrodynamic condition at shallow water area or at the runup area. This study assumes that the landuse correlates to the flow friction coefficient. Here, we interpret the coefficient as the Manning Coefficients (*n*).

At the innermost layer of the simulation, the tsunami hydrodynamic condition are simulated best using nonlinear SWE, as provided from Equations (8) to (10).

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\phi}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \phi}\cos\phi Q\right\} = 0, (8)$$

$$\frac{\partial P}{\partial t} + \frac{1}{R\cos\phi}\frac{\partial}{\partial \psi}\left\{\frac{P^2}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \phi}\left\{\frac{PQ}{H}\right\} + \frac{gH}{R\cos\phi}\frac{\partial \eta}{\partial \psi} - fQ + F_x = 0, (9)$$

$$\frac{\partial Q}{\partial t} + \frac{1}{R\cos\phi}\frac{\partial}{\partial \psi}\left\{\frac{PQ}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \phi}\left\{\frac{Q^2}{H}\right\} + \frac{gH}{R}\frac{\partial \eta}{\partial \phi} + fP + F_y = 0, (10)$$

Spherical coordinates (ϕ, ψ) are for latitude-longitude of the grids at the layers where the spherical coordinate system was employed. Bathymetry data for Layers 1 and 2 were adopted from *1-min* Arc GEBCO (General Bathymetric Chart of the Ocean) data. Meanwhile, for Layer 3, the bathymetry data were taken from the Indonesian Navy Unit for Hydro-Oceanographic Survey (PUSHIDROSAL). Topography data were incorporated from 30-m DEMNAS data published by the Indonesia National Agency for Geospatial Information (BIG).

In this research, we included four historical tsunamis as listed in Table 2. The initial waves created by the four historical tsunamis can be seen in Fig. 4.

Table 2
Simulated sources of tsunami for deterministic simulations.

Source Location	Mag. (Mw)	L (km)	W (km)	Depth (km)	Strike (°)	Dip (°)	Slip (°)	Epicenter		Type	Reference
								Long.	Lat.		
Tanimbar	9.15	230	112	25	220	10	95	136.18	-0.68	Fault	Liu et al
Through	9.15	220	112	20	260	10	95	138.18	-1.51	Fault	2013,
Tanimbar Through	8.4	125	112	25	189	12	95	132.32	-6.20	Fault	Cummins et al, 2020
	8.4	135	112	25	221	12	95	132.33	-7.29	Fault	
Weber Sea	8.4	40	15	-	330	-	14	131.69	-4.81	Landslide	
Banda Detachment	8.4	50	50	10	46	12	285	130.45	-5.97	Fault	
	8.4	50	50	10	21	12	285	130.05	-6.21	Fault	

Tsunami Estimated Times of Arrival

There is no fixed definition for estimated tsunami arrival times (ETA) from the related body of literature. In some cases, the ETA is taken as the time of the $\eta > 0.5$ m at the observed point. However, the Indonesia Tsunami Early Warning System (InaTEWS), managed by Indonesia Geophysical, Climate, and Meteorological Agency (BMKG), estimates the arrival time in the warning when $\eta = 0.5$ m for the first arrival time (Zhang et al. 2009; Syamsidik et al. 2015). This study adopts the ETA definition provided by BMKG for synchronization reasons linked to the community evacuation procedure planned by the city that is relied on the InaTEWS provided by BMKG. As there are a number of ETAs based on several deterministic tsunami simulation results, the shortest ETAs are taken into account for further discussion in this research.

Tsunami Evacuation Readiness of the Ambon City community

Data collection for tsunami evacuation readiness was carried out using a questionnaire survey of 300 respondents, conducted in five sub-districts: Nusaniwe, Sirimau, Leitimur Selatan, Teluk Ambon Baguala and Teluk Ambon. The sample in this study was selected based on the purposive sampling method with the criteria of being the head of the family/representing the household and being at least 17 years old. Exclusion criteria included residents who had lived in the village for less than two years, considering they might have yet to be exposed to much information, training or simulations in order to deal with tsunamis.

In this study, several factors (see Table 3) are considered in assessing community evacuation readiness for tsunamis. The questions given provide alternative answers “Yes” and “No”. Alternative “Don’t Know” answers are available for knowledge-related questions. Data analysis is presented in a descriptive statistical graphic display and percentage summaries.

Table 3
Description of Factor Identified for Tsunami Evacuation Readiness

Factor	Description	References
Knowledge on Tsunami	The signs of the tsunami, information exposure, well-informed about the potential tsunami hazard, local and indigenous knowledge and knowledge sharing.	(Hall et al. 2019; Sugiura et al. 2019; Kubisch et al. 2020)
Evacuation Plan	Identify assembly points, prepare a list of important addresses and phone numbers, develop an evacuation plan and shelter, identify safe area within the house, practice evacuation plans with family, prepare ready-to-eat food that lasts as long as necessary, prepare important and valuable documents, prepare clothing, cash and special needs/family emergencies, prepare a first aid kit and special medications for first aid	(Hall et al. 2019; Kubisch et al. 2020)
Evacuation Exercise	Workshop/ socialization on tsunami mitigation, first aid training, evacuation training	(Chen et al. 2022)
Warning Information	Traditional ways of early warning, local agreements for early warning, early warning sources of information, understanding of tsunami sirens	(Sugiura et al. 2019)
Accessibility	Access to information on preparedness and emergency situations, communication tool during an emergency, transport for evacuation, health facility	(Kubisch et al. 2020; Oktari et al. 2020)

Results and Discussion

Based on the numerical simulations, it is found that the shortest tsunami estimated arrival times, as shown in Fig. 5. The shortest ETAs were mostly due to a tsunami generated from the largest earthquake magnitudes from the Tanimbar Trough (southeast of the Banda Arc). Here, the ETAs are between 37 and 57 minutes. With these, the community along the bay are estimated to have sufficient time to evacuate themselves to higher ground, provided that the community will respond swiftly after the earthquake. As the bay is surrounded by many higher ground places within 500 m from the coastline, the community will be able to evacuate timely if the city traffic can be managed properly. The shortest ETA is located around South Leitimur, to the east direction of the Ambon Bay Area. At this point, the shortest ETA could reach about 37 minutes after the earthquake. In this area, the population number is smaller compared to other sub-districts in Ambon City.

The largest inundation area based on the deterministic simulations was found based on the Tanimbar Trough scenario, as can be seen in Fig. 6. The highest inundation was found around the narrow strait that connects the outer part of the bay to the inner part of the bay. This is also the location of Merah Putih bridge that connects both sides of the bay, as aforementioned. Another area that could have severe tsunami impacts is located in the middle of the Baguala sub-district, named Passo. This area has been recently assigned as the new area of the government offices complex. Passo has a large flat area unlike other parts of the city which are limited by steep ground. Based on the largest simulated scenario, the Pattimura Airport is projected to be free from the tsunami. Nevertheless, some areas near its coasts will be inundated by the tsunami by ~ 2.0 m of tsunami flow depth. Based on the simulations, we could identify that there will be three areas around the Ambon Bay Area that will be severely impacted by the anticipated tsunamis, namely Baguala, Sirimau, and Teluk Ambon sub-districts. A more concerning issue is that these three areas are where main populations of the city live and are the main economy centers of the Province of Maluku.

Tsunami Evacuation Readiness of Ambon City's community

A total of 300 survey participants were community from Leitimur Selatan (n = 58, 19.33%), Nusaniwe (n = 125, 41.66%), Sirimau (n = 56, 18.66%), Baguala (n = 44, 14.66%), Teluk Ambon (n = 17, 5.66%). Of all the respondents, 46.33% were male and 53.66% were female. The respondent's most recent educational background were never attended school (0.33%), not completed elementary school (3%), elementary school graduate (19.66%), middle school graduate (15%), high school graduate (52.33%), academy/university graduate (9.66%). The majority of respondents are currently employed (49.33%) and housewives (30%), while the remaining individuals are unemployed/ not seeking jobs (3.33%), and actively seeking employment (2.66%). The majority of respondents (81.33%) live within a distance of 500 meters from the shoreline, while the remainder reside beyond the 500-meter mark.

One of the important factors in tsunami evacuation readiness is community awareness and understanding of the early signs of a tsunami. As seen in Fig. 7, most of the respondents (81.67%) indicated that an earthquake which causes strong shaking thus rendering people unable to stand is one of the signs of a tsunami. This result indicates that the community in Ambon City already have a good understanding of the relationship between an earthquake and a tsunami. Furthermore, 68.67% of respondents considered the seawater that suddenly receded as a sign of a tsunami. They realized that when the sea water retreats abnormally, it could indicate a tsunami threat. This response reflects a good knowledge of observing natural changes such as receding sea levels. However, tsunamis that occur due to earthquakes are not always marked by receding sea water. The community should not go to the coast to observe the sea level after a big earthquake because a tsunami can occur without the sea level receding beforehand. There is a need for further educate the community about the correct signs of a tsunami. Educational efforts can be focused on the signs of a tsunami providing information about appropriate behavior when these signs occur. Increased public awareness of tsunami signs can reduce the level of vulnerability and increase the level of safety in facing the tsunami hazard.

This study also examines the sources of tsunami information that the community has accessed. The most accessed sources of information are relatives, friends, or neighbors (89.67%). These results indicate that interpersonal communication in a social environment is one of the important and reliable sources of information for the community. Direct and well-understood communication with those other individuals closest to them enables the dissemination of tsunami knowledge. The survey results also show at respondents received information about the tsunami through television (89.33%) and internet/social media (67%), which are both important mediums in the digital era that can reach many people relatively quickly. These results show the importance of television and internet/social media as an effective information channel in conveying knowledge about the tsunami to the public. The research results also reveal various other sources of information the community uses in obtaining knowledge related to the tsunami (see Fig. 8). This result shows that these sources still contribute to disseminating knowledge about tsunamis. Therefore, a holistic approach involving various media and institutions can effectively raise public awareness about the tsunami hazard.

Furthermore, the survey results show that only 4% of respondents know about local traditions and wisdom related to the tsunami. These results indicate that efforts are needed to increase community understanding of local knowledge that can help deal with the tsunami hazard. Up to 50% of respondents had discussed with or informed family members about the tsunami. Hence, there is a need for a more comprehensive education campaign and encouragement to have more discussions and information sharing about the tsunami within the family, in order to build a better-prepared community more capable of dealing with tsunami hazards (Dudley et al. 2011; Lindell et al. 2015).

Regarding the respondents' efforts to anticipate the tsunami hazard (Fig. 9), most respondents (69.33%) were aware of the tsunami hazard around them. Almost all respondents (95.33%) had prepared to provide clothing, cash, and special family needs. The survey results also underscore that some respondents (43%) have conducted tsunami mitigation efforts (such as planting mangroves, etc.). Preparations involving evacuation planning, such as identifying assembly points, evacuation plans, and practicing with the family, still need to be improved, with response rates ranging from 37-57.33%. Only around 24–49% of respondents have prepared important documents, ready-to-eat food that is durable, and first aid kits and particular medicines. More intensive efforts are needed to educate the community about the hazard and mitigation measures that can be taken to improve preparation for the tsunami hazard. A socializing methodology to convey the importance of more comprehensive evacuation planning and emergency preparation is also necessary (Latcharote et al. 2018; Carvajal et al. 2019).

The survey results highlight that around 41.33% of respondents have attended workshops or socialization efforts on tsunami mitigation. Around 16% of respondents have attended a first aid training course. However, only 20% of the respondents had participated in the evacuation drill. These results reveal low community participation in tsunami-related training and drill activities. Therefore, authorities, related institutions, and local communities need to work together to increase community participation through systematic, structured, and sustainable outreach, workshops, training, and evacuation drills in order to strengthen preparedness towards tsunamis.

In terms of tsunami early warning, only a few respondents knew of traditional methods passed down from generation to generation in the community as tsunami early warning (3.33%), and were aware of local agreements regarding tsunami early warning (5.67%). More extensive and intensive educational efforts are needed to expand knowledge about traditional ways, local agreements, and early warning systems in dealing with the tsunami threat. The level of community knowledge about the existence of an early warning system for tsunamis is higher (35.67%) than knowledge about traditional methods or local agreements. Moreover, the survey responses suggest that local governments (71.67%) and places of worship (74.67%) have a significant role in providing early warning information to the public. Community figures, folklore, generations, and personal experience (64.33%) also play an important role in disseminating this information. However, efforts are still needed to increase community understanding and preparedness related to the existing early warning system, and allow the community to take appropriate actions and improve safety during a disaster (Lauterjung et al. 2010; Yuzal et al. 2017; Núñez et al. 2022).

This study also examines the accessibility of the community to several important necessities in an emergency. The survey results indicate that some respondents (33.33%) have access to information on preparedness and emergencies. In addition, respondents stated that they have access to communication tools during a crisis (54.33%), transportation for evacuation (40.33%), and health facilities (44%). These results recommend that there is a need to increase the availability of transportation that can be used for evacuation, especially in disaster-prone areas. In addition, the government and other related parties must increase access to information on preparedness and emergencies, communication tools, and health facilities (Güerena-Burgueño et al. 2006; Rizal et al. 2020).

Conclusions

This research attempts to fill gaps in tsunami research for the eastern part of Indonesia by taking Ambon City as the study area. The research revealed that, based on a series of deterministic tsunami simulations, three sub-districts are subjectable to severe impacts of future tsunamis, namely Baguala, Sirimau, and Teluk Ambon districts. The shortest tsunami arrival times (ETA) in selected locations inside the Ambon Bay Area are between 37 and 57 minutes. With the ETAs, the coastal community in the city will have sufficient time to evacuate to higher ground since most of the higher ground places along the bay are located within 500 m from the coastline. However, concerns are on emergency traffic management of the city which at this point is still not available and is also untested.

Most of the community are well connected to places of worship. They obtain a useful amount of information, including tsunami awareness information, from the places of worship (around 75% of the respondents). Around 81%

of the respondents understand that major earthquakes are sources of tsunami that they should anticipate. However, a very low number of respondents have participated in tsunami drills (around 20%).

Based on the elucidated conclusions, this study suggests to the related stakeholders to improve the performance of tsunami early warning system in the city, compose and test emergency traffic management, and disseminate further the tsunami awareness to younger generations through systematic mechanisms, such as embedding the information into school curriculums.

Declarations

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Figures

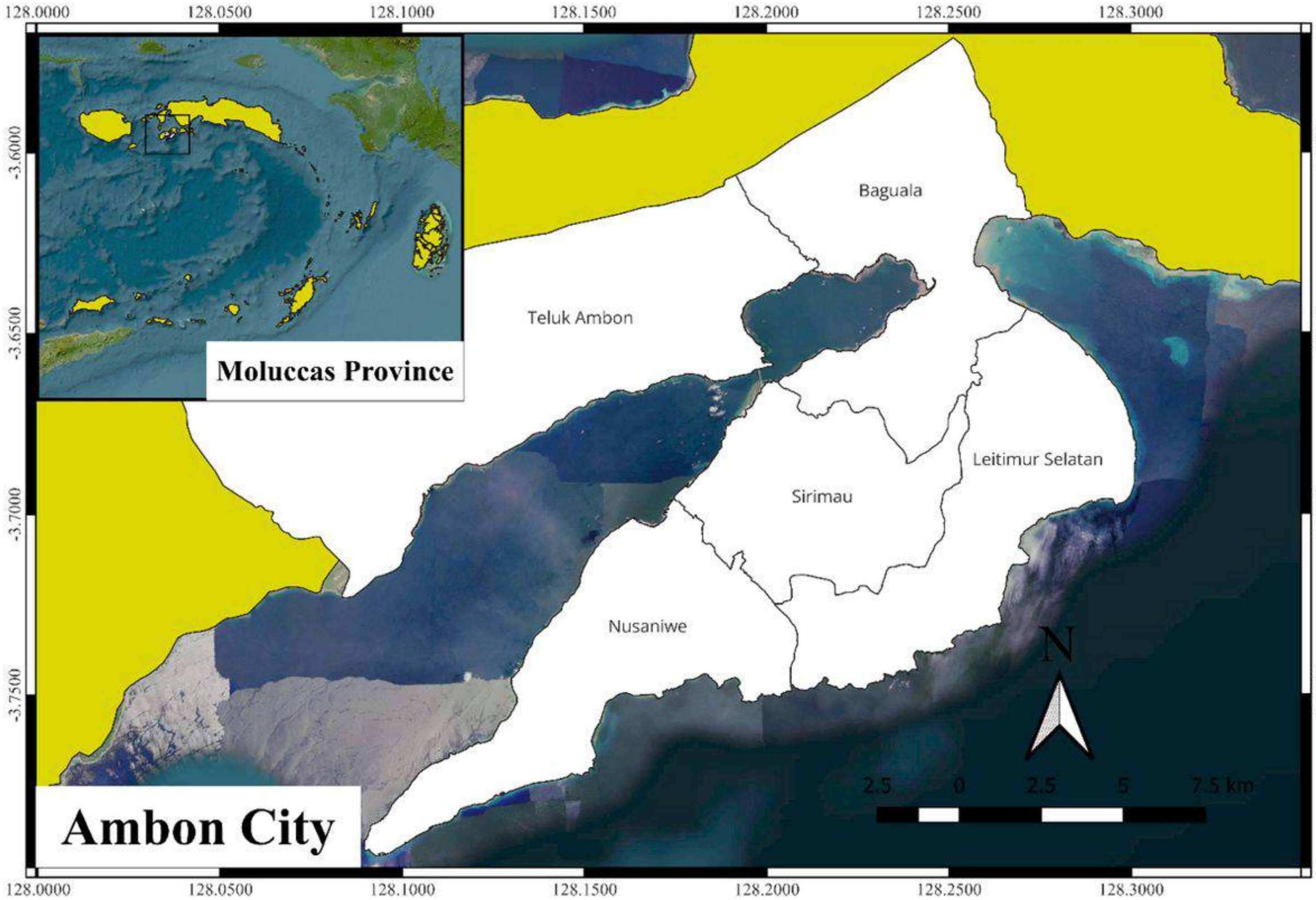

Figure 1

Ambon City in Ambon Bay Area.

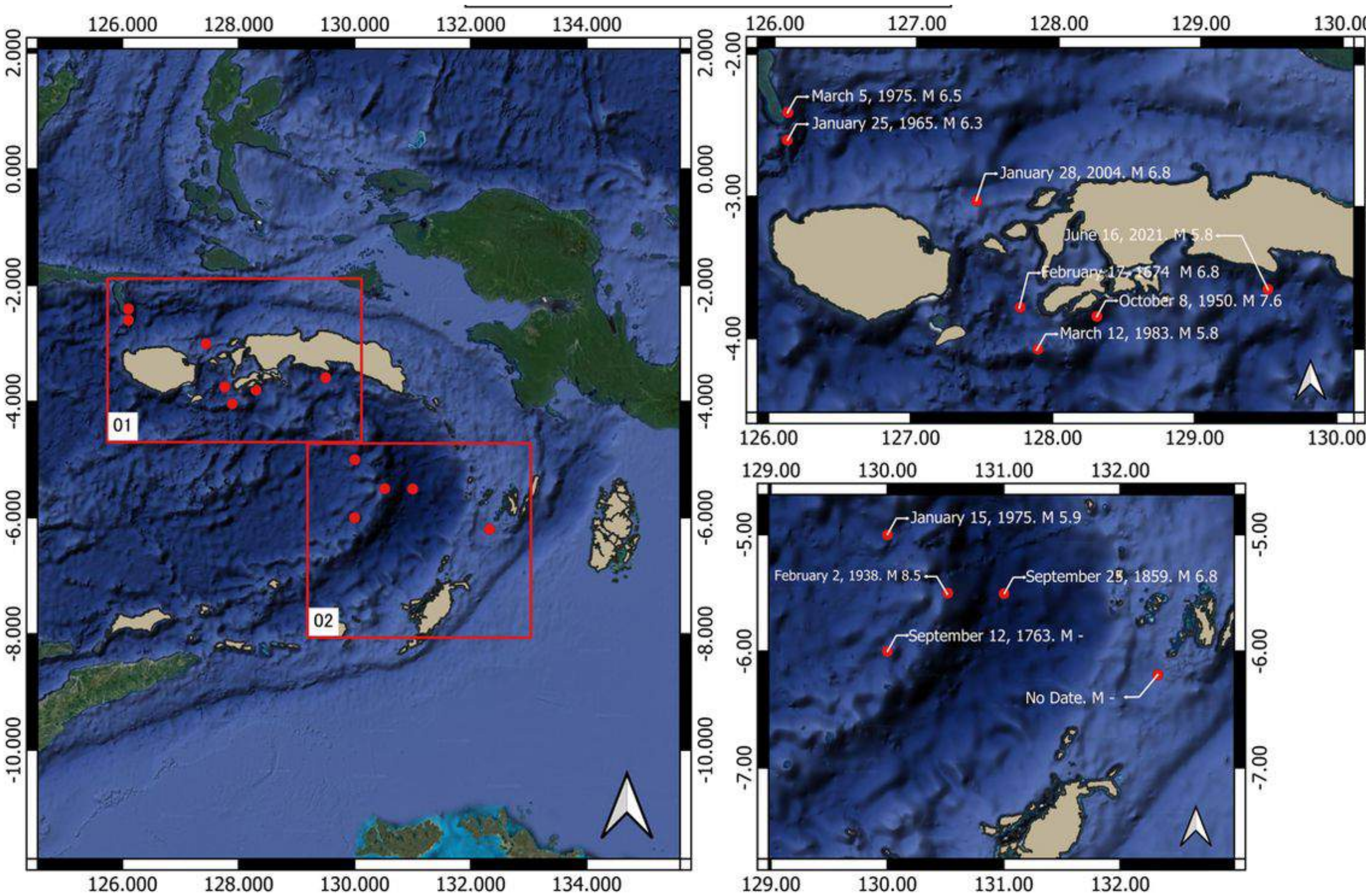

Figure 2

Epicenters of historical tectonogenic tsunamis around the Maluku Province of Eastern Indonesia (in red dots).

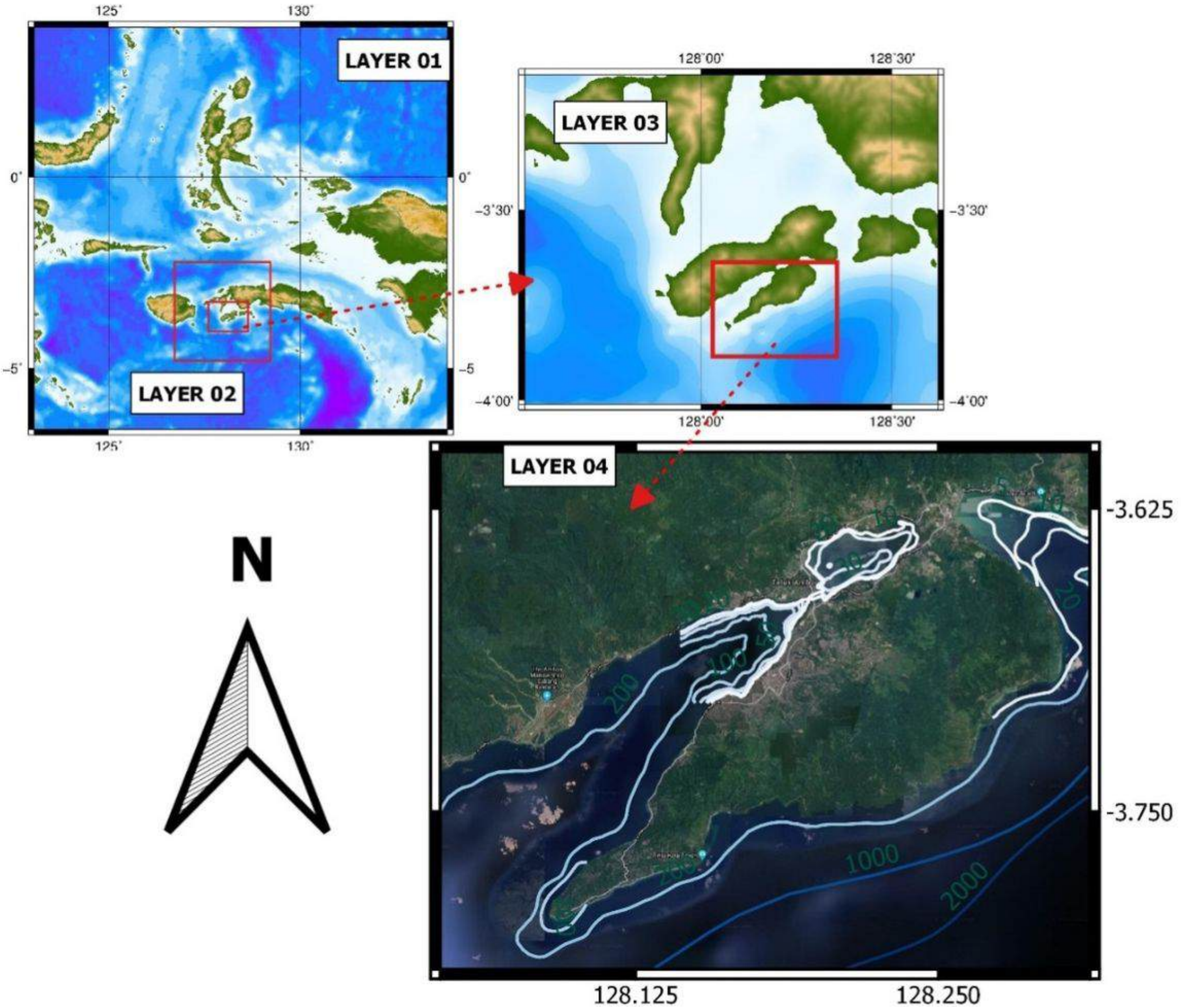

Figure 3

Layers for the numerical simulations.

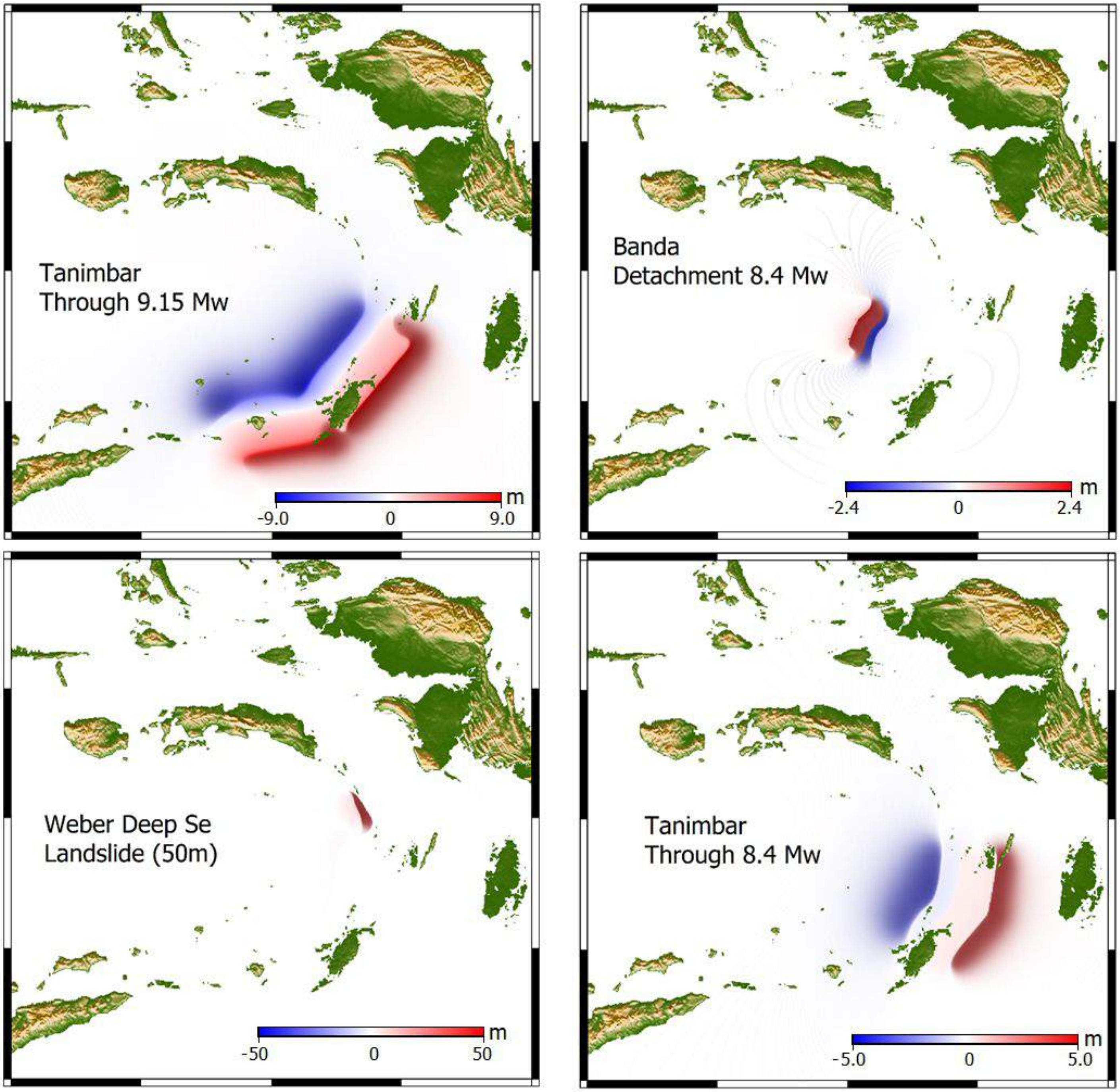

Figure 4

Initial wave forms generated based on the mechanisms of four tsunamis included in this research.

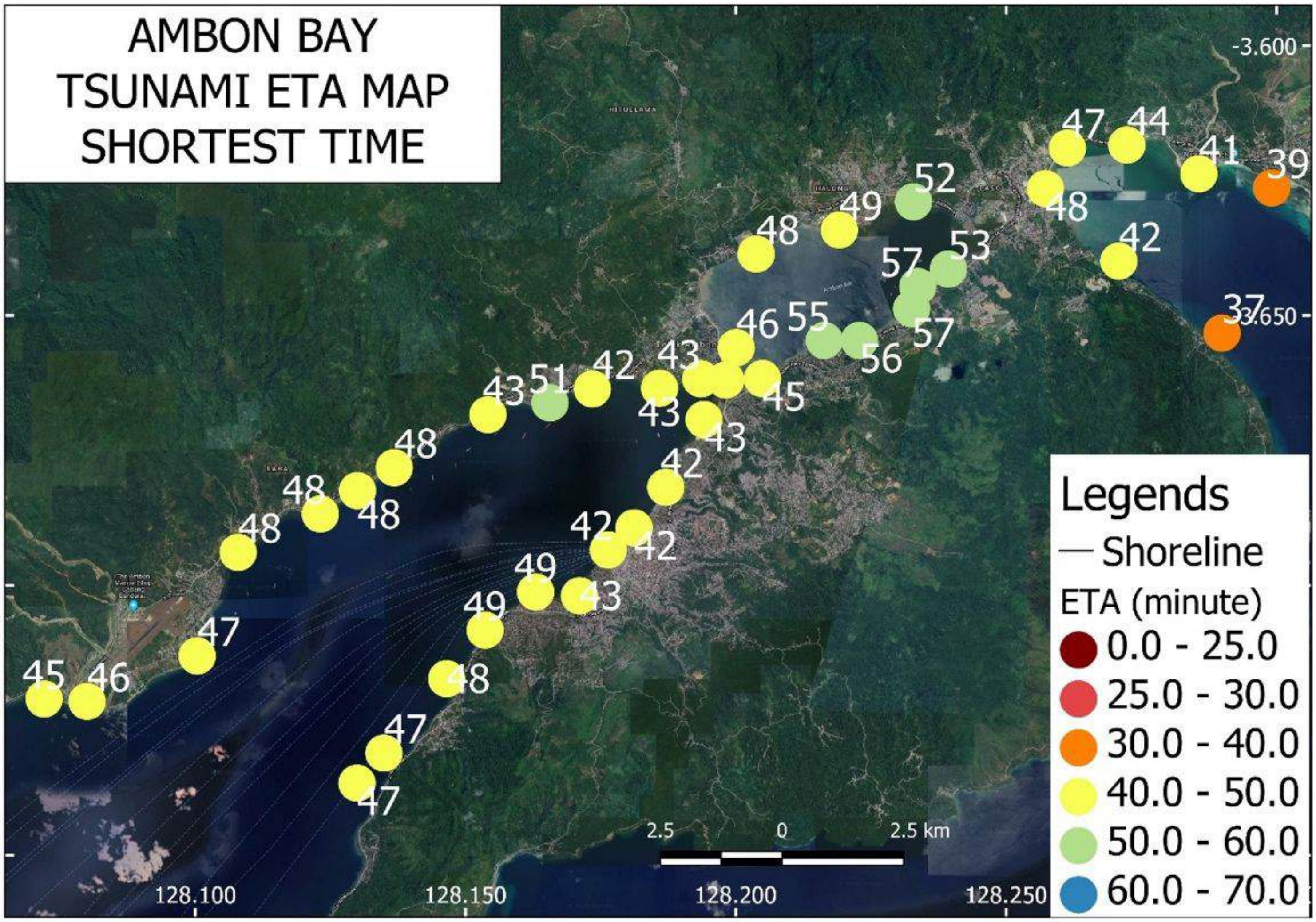

Figure 5

Shortest Estimated Tsunami Arrivals time at selected locations inside Ambon Bay Area based on deterministic models.

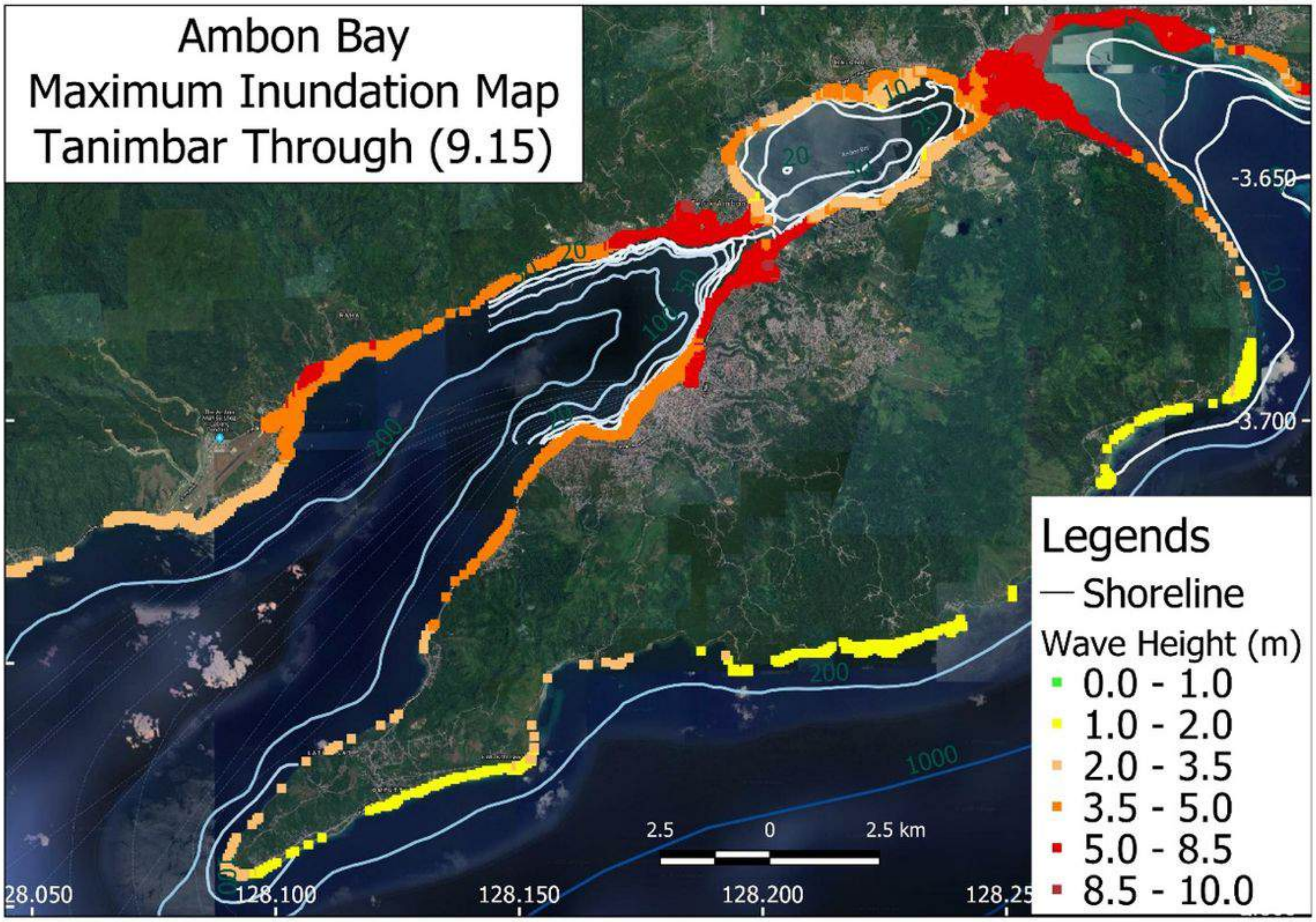

Figure 6

Tsunami inundation map based on the largest scenario generated from Tanimbar Through (9.15 Mw).

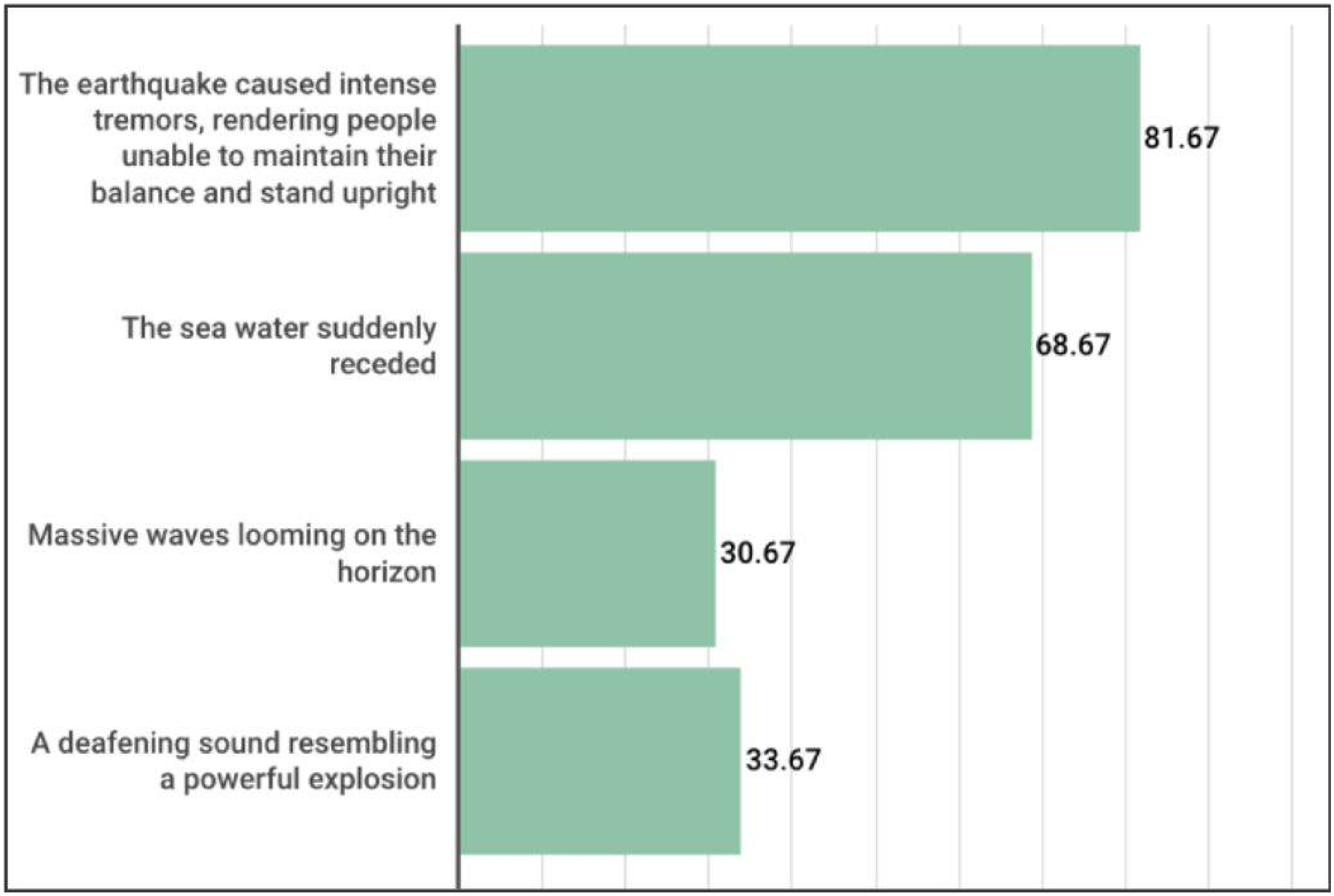

Figure 7

Respondents’ answers related to signs of a tsunami

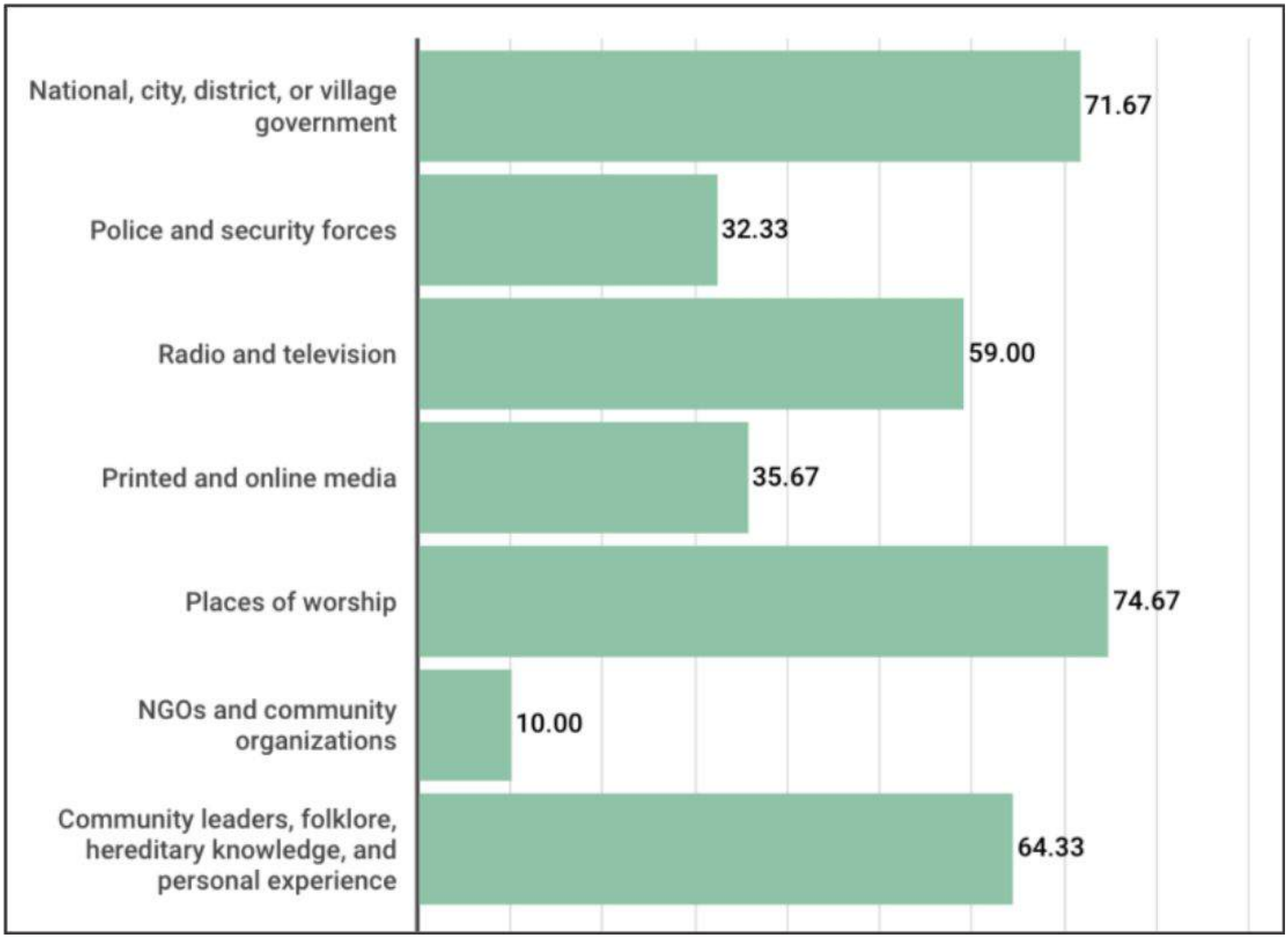

Figure 8

Respondents' answers related to sources of information connected with the tsunami

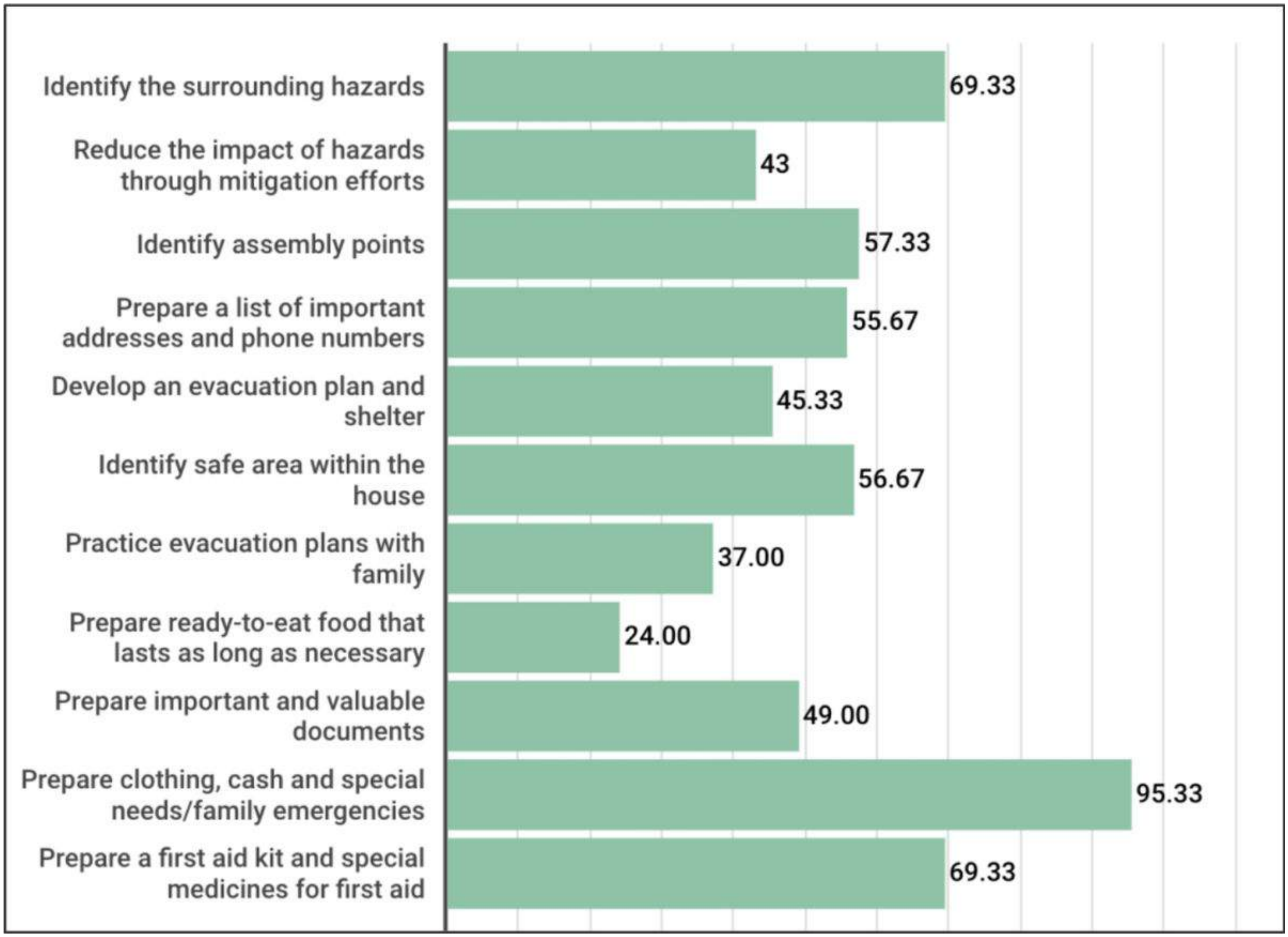

Figure 9

Respondents' answers related to efforts to anticipate the tsunami hazard