Tsunami-induced inundation on the coast of Palu City

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Abstract. The frequency of tsunamis in Indonesia is smaller than other natural disasters. But its destructive power is quite large. Although this disaster has a low probability of occurring, the losses caused by these disaster equated and even exceeded frequent disasters such as floods and landslides. More than 85\% of tsunamis in Indonesia were caused by underwater earthquakes. Thus, mitigation efforts are needed to minimize the impact of the tsunami disaster. The source of the tsunami wave was generated on the Makassar Strait Thrust North Fault. In this study, tsunami was modelled by using Delft3D software. The model approach uses the principle of momentum and continuity. The area of the model was divided into 2 grids. The wave reached the bay mouth in 10 minutes and arrived at the coast of the study area in 20 minutes. The highest peak of water level on the coast occurred in the second wave with an amplitude of 2.45 m and a wave height of 5.19 m. The inundation map was compared to the recorded data from the 2018 tsunami. It was found that there is no significant difference between the two although the tsunami generation were different.

1. Introduction
On 28 September 2018, there was a big earthquake (7.5 M) in central Sulawesi which was followed by a tsunami disaster. The tsunami caused tremendous financial and physical losses [1]. The epicenter is located at the coordinates 0.178 South Latitude, and 119,840 East Longitude. The epicenter distance is 27 km North of Donggala at a depth of 10 km [9].

The tsunami height ranges from 5-7 meters to mean water level (MSL) on the coastline [3]. After the waves break, the wave height becomes 2-3 meters with a distance of several tens of meters inland [3].

There is speculation that large wave tsunamis are the result of secondary sources [3]. Evidence in the field indicates that the tsunami was caused by submarine landslides [9]. The submarine landslides was triggered by an earthquake [9].
The pattern of tsunami propagation direction is very varied. It has a very local nature. This is because of the many tsunami sources [8]. This can be seen from the eyewitness statements that are different [8]. Besides, the debris flow pattern still needs to be investigated more [8]. Based on the results of observations, the earthquake mechanism was in the form of strike-slip with movement to the right [8]. Vertical deformation is not significant for generating tsunamis [8]. The tsunami of September 28, 2018 has been a mystery because an earthquake with strike-slip nature usually cannot produce a large tsunami [3]. Slip-strike does not usually produce a large vertical increase/decrease in the seabed because of the dominant horizontal fault movement. Thus, they are usually unable to produce destructive tsunamis [3]. For example, an earthquake with a Mw of 7.8 in the Wharton Basin in SW Sumatra [3], with a dominant strike-slip mechanism, generated a tsunami amplitude of less than 10 cm at low tide [3].

Based on the earthquake map (PuSGeN) there are 48 active faults in Sulawesi [13]. In this study a tsunami was generated from a submarine earthquake. More than 85% of Indonesia's tsunamis are caused by submarine earthquakes [14]. Tsunami propagation simulation generated from the Makassar Straits Thrust North fault. It located in front of Palu Bay. The tsunami probability of the city of Palu occurring with a tsunami height of 0.5 to 3.0 m is 1/50 to 1/10 [14]. For tsunamis with a height above 3.0 m, the probability of occurrence is 1/500 to 1/100 [14]. Based on the return period, of the tsunami with a maximum height of 1.0 meters to 2.0 meters have a 100-year return period [14]. And tsunamis with a maximum height of 3.0 m to 5.0 m have a return period of 500 years [14]. Therefore, it is highly important to provide a detail inundation map of Palu Coast.

In this study, a submarine earthquake on the coast of Palu is simulated to obtain an inundation map. Additionally, the inundation map is compared to that from the 2018 tsunami. Therefore, the difference of tsunami-induced inundation due to its generation method can be observed. The results of this study are valuable for tsunami disaster mitigation planning on the coast of Palu City.

2. Methods
The source of tsunami generation varies [10]. In this study, the tsunami waves were generated by a submarine earthquake. The fault profile that will be used for the model is sourced from the 2017 earthquake map [13]. The fault used in this model is Makassar Strait North. The fault is located in front of Palu Bay. Based on previous studies these faults have the potential to generate a tsunami [14].

The tsunami wave generation approach uses Delft3D. This model uses the Okada approach (Figure 1). Earthquake scenario parameters were inputted and then were processed in Delft3D. Fault profile input used is dip, rake, strike, length, and width.

Figure 1. The fault parameters used in the model with the Okada (1985) approach on Delft3D (source: Deltares)
Tsunami wave simulation in Delft3D is based on continuity and momentum. The continuity equation is obtained by integrating the continuity equation for incompressible liquids. The continuity equation in the simulation is provided in Equation 1.

\[ Q = \int_{-1}^{0} q_{in} - q_{out} d\sigma + P - E \]  

(1)

Where \( q_{in} \) is the source of entry and \( q_{out} \) out of each grid of the volume unity model (1 / s). P represents rain (m/s) and E is evaporation (m/s). For the momentum equation used in tsunami wave simulation as in Equation 2.

\[
\begin{align*}
\frac{\partial u}{\partial t} + \frac{u \cdot \frac{\partial u}{\partial x} + v \cdot \frac{\partial u}{\partial y} + \omega \cdot \frac{\partial u}{\partial \sigma}}{\sqrt{G_{xx}}} + \frac{\nu^2}{\sqrt{G_{yy}}} \frac{\partial^2 G_{yy}}{\partial \sigma^2} + \frac{uv}{\sqrt{G_{xx}}} \frac{\partial^2 G_{yy}}{\partial \sigma \partial \xi} - f_v &= \cdots \\
\cdots - \frac{1}{\rho_0 \sqrt{G_{xx}}} P_{\eta} + F_{\eta} + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left( vV \frac{\partial v}{\partial \sigma} \right) + M_{\eta} \end{align*}
\]

(2)

\[
\begin{align*}
\frac{\partial v}{\partial t} + \frac{u \cdot \frac{\partial u}{\partial x} + v \cdot \frac{\partial u}{\partial y} + \omega \cdot \frac{\partial u}{\partial \sigma}}{\sqrt{G_{yy}}} + \frac{\nu^2}{\sqrt{G_{xx}}} \frac{\partial^2 G_{xx}}{\partial \sigma^2} + \frac{uv}{\sqrt{G_{yy}}} \frac{\partial^2 G_{xx}}{\partial \sigma \partial \eta} - f_v &= \cdots \\
\cdots - \frac{1}{\rho_0 \sqrt{G_{yy}}} P_{\zeta} + F_{\zeta} + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left( vV \frac{\partial u}{\partial \sigma} \right) + M_{\zeta} \end{align*}
\]

(3)

where:

\( \xi, \eta \) = horizontal, curvilinear co-ordinates
\( u \) = flow velocity in the \( x \) or \( \xi \) direction (m/s)
\( v \) = fluid velocity in the \( y \) or \( \eta \) direction (m/s)
\( \sqrt{G_{xx}} \) = coefficient used to transform curvilinear to rectangular coordinates \( x \) axis (m)
\( \sqrt{G_{yy}} \) = coefficient used to transform curvilinear to rectangular coordinates \( y \) axis (m)
\( d \) = depth below some horizontal plane of reference (datum) (m)
\( \sigma \) = water level above some horizontal plane of reference (datum) (m)
\( \omega \) = velocity in the \( \sigma \) direction in the \( \sigma \) coordinate system
\( f \) = Coriolis parameter (inertial frequency) (1/s)
\( \rho_0 \) = reference density of water (kg/m\(^3\))
\( P \) = hydrostatic water pressure (Kg/ms\(^2\))
\( \nu_v \) = vertical eddy viscosity coefficient
\( F_{\xi} \) = turbulent momentum flux in \( \xi \)-direction (m/s\(^2\))
\( F_{\eta} \) = turbulent momentum flux in \( \eta \)-direction (m/s\(^2\))
\( M_{\xi} \) = source or sink of momentum in \( \xi \)-direction (m/s\(^2\))
\( M_{\eta} \) = source or sink of momentum in \( \eta \)-direction (m/s\(^2\))

This model uses a different tsunami generation source from previous studies. In previous studies tsunamis were generated from submarine landslides [2]. In this study a tsunami is generated from submarine earthquake. The result of the inundation distribution model will be compared with the
recorded tsunami data from previous study. The comparison is conducted to observe the effect of different generation mechanism to the tsunami-induced inundation.

3. Bathymetry and land topography
Tsunami model uses two data resource, General Bathymetric Chart of Ocean (GEBCO) and Geospatial Information Agency (BIG, Indonesia). Data is obtained in the form of Digital Elevation Model (DEM). The model is used in nested form. The simulation is done by dividing the model into 2 domain, domain A and domain B (Figure 2). Domain A uses GEBCO bathymetry data (Figure 3) whereas domain B model uses bathymetry and topographic data from BIG (Figure 4). Tsunami model inundation nesting processes need high resolution data [6]. Topographical information on coastline and bathymetry near the coast plays an important role. To improve the accuracy of predicted run-up altitude and tsunami inundation [6], domain B uses BIG data with a data resolution of 5 m.

![Figure 2](image)
Figure 2. Model domain of study area with the red square is Domain A and the purple square is Domain B. (Source: Google Earth)

4. Model domain and setup
Tsunami wave simulation uses two domains (Figure 2). Domain A uses a grid size of 500 m x 500 m and domain B uses a grid with a size of 50 m x 50 m. The initial condition tsunami waves are in domain A and afterwards, waves propagate to the Palu bay. The waves travel to the Palu bay in Domain B. Tsunami wave propagation uses nesting. The source of the earthquake generated by the tsunami wave is located in front of the Palu bay. It should be noted here that the source of this tsunami is not the same to that of the 2018 tsunami.

In this study, tsunami wave simulation uses Makassar Strait Thrust North Fault. The distance of the source of the earthquake to the mouth of the bay is around 67 km. The fault profile uses the 2017 Indonesia Earthquake Hazard Map. The map source is from the National Center for Earthquake Studies (PuSGeN, Indonesia). Large slip-rate fault value is 2 mm/year with reverse-slip fault mechanism. The largest earthquake that ever happened was 7.1 M. The depth of the earthquake epicentre was 10 km with 45E dip conditions and 100 km fault length. The profile of the earthquake generated tsunami at the initial conditions of 1.8 meters (Figure 6). Boundary conditions in domain A are open boundaries. The value of manning roughness is 0.01, uniform.
Figure 3. Bathymetry and topography of Domain A obtained from GEBCO with the green square is Domain B

Figure 4. The bathymetry and topography of Domain B obtained from Geospatial Information Agency (BIG, Indonesia)

Figure 5. The location of the tsunami wave observation point results in model simulation

The observation points on the model are placed at the bay mouth and the coast of the study location. At the mouth of the bay, three observation points are placed. One is in the middle of the mouth and two are located on the right and left side of the mouth. Furthermore, three points are located on the coast of the study site. Details on the location of the observation points are presented in Figure 5.
This study focuses on Palu City, Central Sulawesi. Inundation results from tsunami wave model simulation were compared with 2018 tsunami trail measurements.

5. Results and discussion

When tsunami waves propagate to the coast, wave transformation occurs due to continental slope and near-shore slope [12]. In Figure 7, tsunami wave height when the waves propagate from the mouth of the Palu bay to the city of Palu is shown. An increase in tsunami wave height occurs during propagation. The cause of the increase in tsunami wave height is due to the shoaling effect [12]. Changes in tsunami wave heights depend on the slope of sea bed profile [12].

Tsunami wave propagation from source to arrive at the mouth of Palu Bay takes 10 minutes (Fig. 8) with the highest tsunami water level of 1.13 m in the middle (Point 2) of the bay mouth which occurred at 00:13:09. The height of the highest tsunami wave in the middle of the bay mouth is 1.91 m with an 11-minute wave period. At the points located on the right and left sides of the mouth (Point 1 and 3), the bay has a higher amplitude than Point 2. Point 1 has the highest wave amplitude with 1.50 meters which occurred at 00:13:24. The highest wave at Point 3 is 1.30 meters which occurred at 00:13:21. Besides, the largest tsunami wave height at Point 1 and 3 is higher than Point 2 with 3.62 meters for Point 1 and 2.22 meters for Point 3. The wave period when the wave reaches greatest height at Point 1 and 3 is shorter compared to Point 2 which is 7 minutes 12 seconds for Point 1 and 10 minutes 12 seconds for Point 3. In Fig. 8, it can be observed in the first hour on the Point 1 that changes in sea level are greater than those in Point 2 and 3. The wave period in Point 1 tends to be greater than in Point 2 and Point 3.
Figure 7. a) Snapshots of tsunami simulations in domain A (left) at different times; b) Snapshots of tsunami simulations in domain B (right) at different times.

Figure 8. Water level at the observation point in the mouth of the Palu bay (detail of the location of the observation point in Figure 5)
From Figure 9, it can be observed that a tsunami wave arrives on the coast (Point A) at 00:23:09 with the first wave amplitude of 2.45 m and a wave height of 5.16 meters. Whereas at Point B, the first wave reaches amplitude at 00:22:30 with an amplitude of 1.42 m and a wave height of 3.46 m. At Point C, the first wave reaches amplitude at 00:21:49 with an amplitude of 1.66 m and a wave height of 4.03 m.

The wave reaches the largest amplitude on the second wave (Figure 9). At Point A, the largest amplitude occurs at 00:48:24 with an amplitude of 2.88 m and the maximum wave height of 5.58 m. Whereas at the second wave at Point B and C, the amplitude and wave height are lower than those at Point A. The largest amplitude that occurred at Point B is 1.95 m which occurred at 00:48:34 and 2.27 m at Point C which occurred at 00:47:09. Furthermore, the height of the second wave at Point B and C is 4.19 m at Point B and 4.79 m at Point C.

In the third wave at Point A, the wave amplitude and wave height are lower than the second wave. The amplitude of the wave at the second wave at Point A is 2.24 m which occurred at 01:15:06 and the height of the third wave is 5.19 m. However, at Point B and C, the wave reaches a maximum amplitude and wave height in the third wave with an amplitude of 2.19 m at Point B that occurred at 01:15:46 and 2.25 m at point C that occurred at 01:15:31 and the wave height on the third wave is 4.37 m at Point B and 4.80 at Point C.

The tsunami inundation map was compared to the recorded data from the 2018 tsunami [2]. The difference of highest inundation measurement and model is relatively small with a difference value of 0.05 meters. Interesting to note that they were generated from different source of tsunami. The measurement point of the inundation trace is overlaid with the model results as shown in Figure 10. Their difference was calculated at each measurement location as given in Figure 11.

In general, inundation distribution from the model is similar to the measurement traces in the field. It should be noted here that the source for the two tsunamis are different. Thus, it is safe to assume that a tsunami generated from a submarine earthquake possess similar hazard. The highest tsunami inundation height from the model is 3.65 meter, whereas the highest recorded tsunami inundation is 3.7 meter. It is also observed that the area near the river mouth has the biggest difference, especially on the right side of the river. Regardless of the tsunami generation source, the interaction of tsunami wave propagation with the river mouth is not similar to that overland [15]. Additionally, the difference in inundation height is due to a structure at that location. There was a large bridge support as described in a previous study [1]. It should be noted that the tsunami simulation in this study is based on topographical and bathymetry data. The data does not cover structure and vegetation height. Structure and vegetation can minimize the impact of damage due to tsunami waves [16]. Vegetation conditions affect the roughness value [17].
6. Conclusions
Tsunami simulation on the coast of Palu City has been conducted. The source of the tsunami was a fault, located at the entrance of Palu Bay. The initial tsunami, generated by the earthquake, reaches 1.5 m. The tsunami propagates and arrives at the mouth of the Palu bay with a 1.6 m height. The maximum wave height upon arrival at the coast is 3.65 m. It was found that the tsunami height at the coast is similar to that of the 2018 tsunami, although they are of different sources. The time needed for tsunami waves to travel from the source to the mouth of the bay, which is 62 km away, is 10 minutes. The time needed for the tsunami to travel from the mouth of the bay to arrive at the study location (Palu City), which is 32 km away, is 12 minutes.

Inundation distribution from the model approaches the measurement of tsunami inundation footprint. However, there is a difference in the height of a puddle at the mouth of a river because at the estuary, there is a bridge pillar. Tsunami wave model simulation only uses topographic and bathymetric data. The model does not consider the existence of this structure.

The inundation map from the tsunami wave simulation provides important information. The simulation results are useful for the mitigation process of Palu City. However, it is necessary to model tsunami waves from various sources. Modelling can be carried out for various tsunami scenarios. Further research is needed on tsunami modelling by considering structural and vegetation factors in order to obtain a more accurate inundation distribution map.

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