Analyzing Tsunami Hazard using Numerical Modelling: Study Case Palu, Sulawesi Tengah, Indonesia

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Abstract. The present study aims to assess the Tsunami hazard in Palu due to the future Tsunamigenic event in terms of near-shore and far-field Tsunami runup, inundation height, and Tsunami arrival time along the coast of Palu. A numerical model is developed to simulate propagation and inundation in the study area. Four scenarios are conducted, which consists of the Tsunamigenic earthquake and aerial subsidence as an approach for mimicking hypothetical potential landslide. The outcome from simulation such as inundation height each grid points then calculated with building footprint stored data – derivation data from the terrain model to develop a Tsunami hazard map. Preliminary Tsunami Hazard Map is made to classify the Tsunami hazard level by existing classification added with estimated building impacted and arrival time ashore on each village in Palu City administrative region.

1. Introduction
The Tsunami in Palu, located at Sulawesi Tengah Indonesia, (Figure 1) on September 28, 2018, portrays a complex Tsunamigenic scenario where the earthquake might not be the primary cause of the Tsunami. A sinistral strike-slip plate boundary fault system like Palu-Koro rarely produces a devastating Tsunami. The motion of strike-slip faults is caused by shearing forces and have dominant horizontal deformation. It could not provide large vertical uplift on the seabed to make a sudden move for the water column above it and produce a large Tsunami. The earthquake magnitude itself is relatively considered as small in the context of Tsunami generation. Nonetheless, the earthquake could be a contributor for a multi-following peril – multiple submarine landslide and liquefaction in deltaic soils failure, which in this case could have a higher contribution to generating a Tsunami. One similar incident to this case is the 2010 Haiti earthquake, where research shows that even strike-slip earthquakes, can generate Tsunamis triggering aftershocks [1]. In Palu Tsunami case, some researchers conduct a post-disaster field survey and identify sites of potential subsidence along the coast [2].

Even though disaster is inevitable, the risk could be reduced. Tsunami is considered as a rare event and unique from its generation and impact towards the affected area. From one case to another, a lesson learns could be taken to improve either disaster awareness on society or mitigation action that ought to be performed [3,4]. Tailoring strategies to set a countermeasure the disaster is one key to reducing its risk. Nevertheless, examining the mechanisms and phenomena of disasters that occur could be an effective step – even though it is a longer project. Implementation of the Tsunami Hazard Map could
be one of the key preliminary stages to raise awareness on Tsunami disaster risk reduction and spatial planning for coastal cities.

A Tsunami hazard map shows Tsunami affected area both in the context of its inundation depth and coverage. It calls for reference to evacuation planning strategies and set up a warning system. This product also an essence for spatial planning to set mitigation from Tsunami impacts. Based on the 2018 Palu Tsunami experiences, deprivation of Tsunami hazard maps, evacuation systems and miscarriage of warning systems leads to the high loss of life. The current advanced warning system is still hardly preventing huge casualties and catastrophic losses from the Palu case since Tsunami came faster than the warning itself. One of the preliminary stages for avoiding the damage is to identify uncertainties in Tsunami arrival times and potentially inundated areas. As most of the Tsunami hazard maps generally only visualize the impact of the worst possible scenario, this recent event proves that other sources' mechanisms could also cause fatal damage. A tsunami hazard map could be an effective medium to deliver far-reaching information for fulfilling disaster mitigation strategies in spatial planning policy. To help such efforts, this study is posed to address Tsunami parameters for various sources shown in the Tsunami hazard map.

Figure 1. Map of Earthquake Epicenter in Sulawesi September 28, 2018
(Data Source: Badan Nasional Penanggulangan Bencana with modification)

2. Materials and Methods
The general objective of this research is to determine Tsunami prone areas based on inundation depth and its implication towards mitigation disaster action in Palu City. To do this, a numerical model to simulate the propagation of the Tsunami wave is performed. The submarine landslides were
assimilated by using an empirical approach to executed the initial water wave. The hydrodynamic models using Delft3D-FLOW are set to compute Tsunami propagation and inundation [5]. Delft3D-FLOW is one of the most established models for conducting Tsunami simulations which has been validated for several Tsunami events such as the 2004 Aceh Tsunami [6]. This modeling tool can show maximum runup and flood depth for the specified domain area.

2.1. Numerical Model
The Global Domain model grid is developed to represent the various source scenarios that may potentially impact Palu City from outside the bay. It covers from 3° 33' 45.3433" N to 3° 56' 15.7605" S latitude and 116° 15' 31.5033" E to 124° 18' 52.2784" E longitude. With 221,125 rectangular grids counted, each grid has 1.11355 km-length and covers 1.24 km² area. The domain also rotates 10° to embody North Sulawesi Megathrust. This domain is not able to compute inundation on dry land. Global Domain is illustrated as in Figure 2 below.

The Regional Domain grid is used to investigate Tsunami behavior during propagation into the land area and generate possible landslide submarine-induced Tsunami generation scenarios within the bay. It spans from 119° 40' 19.4641" E to 119° 53' 56.7096" E longitude and 0° 34' 11.0964" S to 0° 54' 21.3421" S latitude. Each grid covers 0.01534 km² with 122 m length of a rectangular grid.

To connect the two domains, Delft3D-FLOW has a Domain-Decomposition (DD) boundaries feature [5]. DD boundaries are a feature as internal boundaries to communicate between separate models. DD boundaries connect the wide-area model and regional area model which is separated in the mouth of Palu Bay. This regional area model is developed by subdivision from the Global area model using domain decomposition technique. Thus, the model can be divided into numbers of smaller model domains.

The local Area grid is the refinement of the southern part of the Regional Domain model. Higher grid size resulting in less accurate in the calculation of flooded area. The grid is simplified into a rectangular of 40 m by 120 m. This horizontal refinement is deliberately to identify Tsunami propagation in shallow water areas onshore and provide better inundation parameter information. The grid in a shallow water area will be smaller compare to the deep ocean zone to give a satisfactory result. The farthest inland area only covers up to 2.3 km to the North East area. Figure 2 illustrated the Global and Regional Domain as well as the Local Area.

Palu Bay area has a complex and unique contour. The geomorphology of it beneath the sea surface is not flat. It shapes a ravine filled by an alluvially deltaic system from each mountainous side. Palu Bay has a 30 km-length with 7 km-width. Its thalweg is reaching up to 700 m along the bay. Bathymetry data in this study are compiled from several data sets. The GEBCO_2014 bathymetry dataset is available at 30-arc seconds resolutions (0.926 km) [7] and applied as preliminary bathymetry information for the deep-water area. Some areas are covered by other finer bathymetry data replacing them whenever it is available. The bathymetry of the entire bay of Palu was surveyed in 2014 and shared publicly by the BIG [8] (tides.big.go.id/DEMNAS). Some primary survey had been conducted by Indonesian agencies as well as researchers [9]. Coastal Research Group from the Ministry of Public Works and Housing had been surveying bathymetry along the southern part of the Palu waterfront area. Badan Pengkajian dan Penerapan Teknologi (BPPT) had also made a primary observation to obtain a higher resolution of bathymetry data in Palu Bay. All bathymetry data are representatively shown in Figure 3.
2.2. Tsunami Sources
Any sudden disturbance factor that could deform a large water mass vertically in the sea from its equilibrium position can generate a Tsunami. Such sudden disturbance caused by geological process: earthquake, landslides, volcanic eruptions, or astronomical events like meteoritic impacts. A Tsunamigenic earthquake happens due to seafloor plates moving against each other. There are only three types of faults that can generate a Tsunami: a strike-slip earthquake on a vertical fault, a dip-slip
earthquake on a vertical fault, and a thrusting earthquake on a dipping plane. Landslide generated tsunami is mainly caused by an earthquake-triggered submarine-landslide in steep bathymetric. Submarine landslide is generally proclaimed as a cause of surprise tsunami. The surprise tsunami can be generated by even smaller expected earthquake magnitude and far away from the epicenter.

Tsunami modeling has long-established been performed in scenario-based. Modeling outcomes rely on available information and data. Even though reality condition contains a complex parameter, scenarios can be created to generated various alternative output and be able as comparison tools of options. In other words, scenarios here are functioned to simplify the complexity to produce an understanding.

A zero-water level is prescribed at the beginning of the simulations in all cases as only water level propagation is the only parameter considered in the modeling. The initial condition is the water surface perturbation at the initial time of the simulations which can be caused by Earthquake along the Faultline or landslide, e.g. using Okada (1975) [10].

Figure 4 shows the map of Faultline surrounding Sulawesi Island. Based on this, three simulation scenarios based on Faultline are carried out. North Sulawesi Subduction Zone (NSSZ), North Makassar Thrust (NMTH) and Palu-Koro Faultline Supersheer (PKFS) are based on previous studies [11-15]. The detail Faultline parameter for simulation scenarios can be seen in Table 1.

In comparison to earthquakes, there are many parameters such as slump density, total distance moved, grain size, material density, which are particularly difficult to observe, especially for the submarine landslide. Murty (2003) has identified a simple relationship between the volume of a landslide \( V \) and maximum resulting tsunami wave height \( H \) based on observational data in published literature and numerical model [16]. He hypothesized that simply landslide volume is a key parameter that should exist as the source of tsunami by mathematical expression as in (1),

\[
H = 0.3945 V
\]  

By conducting calculation using spatial analysis tools, there is an estimated 3,976,358 m\(^3\) of coastal land subsidence. Therefore, the initial water level height is obtained with 1.57 m. Therefore, 1 (one) simulation scenario based on a possible landslide location in Pantoloan is added. The location can be seen in Figure 4.

| Scenario ID | Mw | Longitude (deg.) | Latitude (deg.) | Segment (km) Length Width | Depth (km) | Strike (deg.) | Dip (deg.) | Slip (deg.) |
|-------------|----|------------------|-----------------|--------------------------|------------|---------------|------------|-------------|
| NSSZ        | 9  | 120.166          | 1.577           | 200.53 110               | 30         | 72            | 20         | 90          |
| NMTH        | 8  | 119.1724         | -0.3731         | 100.53 50                | 20         | 11            | 20         | 90          |
| PKFS        | 7.5| 119.1724         | -0.3731         | 100.53 50                | 20         | 11            | 20         | 90          |
3. Results and Discussion

3.1. Initial Water Level Condition and Tsunami Propagation

The result of the formulation of the Okada (1975) based on the Faultline parameter in Table 1 creates an initial water level. For example, North Sulawesi Subduction Zone (NSSZ) creates as high as 4.97 m along 200 km continuously in the Celebes Sea in semi-spherical shape. Whereas, North Makassar Thrust (NMTH) creates an initial water level as high as 1.4 m along 100 km continuously in the Makassar Strait in semi-spherical shape, 33 km far from Palu Bay mouth. The Palu-Koro Faultline Supershear (PKFS) case only generates water level deformation to 1.17 m in two-bubble shaped. Different from the previous scenario, Scenario 4 does not use Global Domain and uses a different approach for generating water level in Local Domain. The initial water level is input manually and creates with the same shape as its possible landslide dimension. The initial water level for all scenarios is shown in Figure 5.

3.2. Model Verification

Any research comprehensive scientific journal which explained in detail regarding Tsunami numerical modeling in Palu area is considerably limited and consists of assumptions (e.g. [17]). The present model numerical scheme and setting parameters are based on Van Veen et al., (2006) [6]. Besides, the present model results can be accepted, qualitatively, based on hydrodynamic consideration. Hence, giving the Tsunamigenic source, the Tsunami propagation and inundation can be deemed valid.

3.3. Tsunami Propagation and Inundation

As the scenario NMTH gives the worst result, Tsunami propagation and inundation are illustrated based on this scenario. For this scenario, the first wave starts entering the Palu Bay from minutes 7 after the earthquake occurred. As happened in the previous scenarios, the water level takes around 8
minutes to reach the tip of Palu Bay in the Silebeta area. Nevertheless, the water level begins to increase as the passes Pantoloan and reach the Silebeta area with water level twice higher than its former condition. The snapshot of water level propagation in the Global Domain and within Palu Bay area is illustrated in Figure 6.

**Figure 5.** Initial water level condition showing for scenario a). NSSZ; b). NMTH; c). PKFS and d). Landslide at Pantoloan

**Figure 6.** Tsunami propagation after 7 minutes in Global Domain (left) and 15 minutes in Regional Domain (right) for the scenario NMTH
The inundated height is then extracted and presented in the form of Inundation Map. Highest inundation point is found in Buluri Village with 3.6 m and maximum runup reach for 45 m from the coastal line. As contrast with Buluri village, maximum runup is found in Lere village whereas 3.5 m is identified as maximum inundation height. Furthermore, 2.2 km along the Palu River is inundated. However, two villages adjacent to Palu River in upper Stream – North Lolu and Ujuna, do not get any significant impact. The topographical condition reveals that both villages have a steep slope and higher elevation on the riverbank area makes them do not suffer severe damage in this scenario. The eastern part has no significant impact as well as the western part. Many 0.2 m inundation height points have been found in Wani. The inundation map for Silabetta area for Scenario NMTH is illustrated in Figure 7.

![Inundation Map in Local Area Model for Scenario NMTH](image)

**Figure 7.** Inundation Map in Local Area Model for Scenario NMTH

### 3.4. Preliminary Tsunami Hazard Map

Tsunami hazard is one of the major concerning issues in Indonesia. In the past century alone, there have been 24 Tsunami events that occurred in Indonesia. One of the purposes of hazard maps is to provide residents with appropriate and sufficient information on disaster prevention to help them act appropriately at the occurrence of the disaster. To this end, Geological Agency has released a Tsunami hazard map that classified the hazard into three-level: High Tsunami hazard zone, Moderate Tsunami Hazard Zone and Low Tsunami Hazard Zone [18]. The classification is based on its inundation depth, which less than 1 m inundation is considered as a low Tsunami hazard zone, 1 to 3 m categorized as moderate Tsunami hazard zone and more than 3 m is considered as high Tsunami hazard zone. Based on research conducted by previous researchers [19,20], the inundation area is calculated in a grid size of the Local Domain (40 m x 120 m) to measure the Tsunami hazard level. The tsunami hazard level
used is based on the definition made by the Geological Agency. Based on that, the number of buildings that have tendencies to be impacted by a certain level of Tsunami hazard is counted. This calculation was conducted for each sub-district and Tsunami arrival time was also provided.

Preliminary of Tsunami Hazard Map in Lere Village is shown in Figure 8.

Figure 8. Preliminary Tsunami Hazard Map

4. Conclusions
The general objective of this research is to determine Tsunami prone areas based on the inundation depth and its implication towards mitigation disaster action in Palu City. To do this, a numerical model has been developed. Tsunami inundation modeling using four source scenarios is carried out to determine the Tsunami area for the coastal region of Palu.

Despite a parallel Faultline with Palu Bay, the scenario of North Makassar Thrust (NMTH) turned out to be inducing the most destructive result compare to other scenarios designed. Gentle slope bathymetry profile in front of Lere and Silae coastal region indeed caused the Tsunami wave flows rushed onshore rapidly and drawback in a long time. Palu River itself contributes to inundating adjacent areas. A more comprehensive check-in topographic dataset is required to identify whether it is natural terrain or misinterpretation from spatial analysis erroneous.

Numerous parameters should be considered to generate submarine or aerial landslide-induced Tsunami to give a more satisfactory result. One large landslide will in fact not produce significant deformation of water level as it propagates when it does quite far within the bay. The impact certainly felt on the land opposite.

Nonetheless, high-resolution topographic data is crucial to give more detail and accurate inundation area. Building attributes such as building height information extracted from high-resolution topographic datasets might be useful in the future to develop a Tsunami hazard map. This information can derive analysis such as Tsunami impact towards building on a macro scale or to determine which Tsunami-prone building corresponding to the level mentioned.

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