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Characteristics of Sediment Transport After Morphological Changes at Palu Estuary, Sulawesi, Indonesia as The Impact of 2018 Tsunami

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Abstract: The tsunami triggered by the 2018 Palu Earthquake has not only caused the collapse of public infrastructure, but also damaged beaches along Palu Bay. Based on direct investigation along the beaches, the coastlines have shifted inland up to 30 meters. This shoreline change was caused by the attack of the tsunami waves at high speed followed by massive abrasion. Another impact of the wave attack is a change in the morphology of the beach bed, including in the Palu Estuary. This study aims to investigate the impact of changes in bed morphology around the Palu Estuary as a result of the tsunami attack on transport sediment characteristics, as one of the determinants of bed morphology. Quantitative analysis was carried out by numerical simulation based on 2D hydrodynamic modeling using the Surface-water Modeling System (SMS). The geometry of the model is formed from the mesh generated from the bed elevation based on the after-tsunami bathymetry survey. Two boundary conditions and one main input data are applied to this model: discharge data, tidal data and bed load data. Discharge data as an upstream boundary condition consists of minimum discharge, average discharge and maximum discharge. The downstream boundary is defined by a tidal curve predicted from 15 daily data. The bed load data is presented in the form of a gradation curve that describes the distribution of sediment grains. The simulation output indicates that sediment settles intensively downstream of the river mouth at high discharge and low tide. At low discharge and high tide, sediment tends to settle before the flow reaches the river mouth. Referring to the results of previous studies, the direction and velocity of sediment motion changed slightly after the tsunami. Changes in the direction and speed of movement are related to changes in bed morphology at the river mouth due to the 2018 Palu Tsunami.

Keywords: Sediment deposition, 2D hydrodynamic simulations, river mouth, bed subsidence

1. Introduction

Sediment transport is a topic that remains interesting to be studied today [1]-[3]. Apart from being unique due to the high uncertainty and complexity of the variables that influence it, the prediction method that has been developed is also not very satisfactory. Various approaches have been accommodated to reduce deviation in developing the transport formula. On this basis, transport studies with various approaches are still very open to being implemented.

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2D modeling with hydrodynamic simulation is a more acceptable approach. Parameter complexity and geometric irregularities can be better accommodated in the model [4], [5]. The basic configuration of natural domains such as rivers and beaches is generally very irregular, even the basic morphology can change rapidly due to flash floods, tsunamis and various other natural events that affect the intensity of the transport.

The Palu River Estuary is one of the cases where the bed morphology has changed significantly. The tsunami waves triggered by the earthquake have eroded most of the sediment deposits at this site [6]. The waterbed becomes deeper by more than 2 meters due to degradation. This configuration change has the potential to affect the transport intensity such as the rate and direction of deposition along with the fluctuating tides in the estuary.

At least four studies on the sediment transport analysis due to morphological changes with 2D hydrodynamic simulations have been carried out at the same location. Madman [7] and Antariksa et al. [8] conducted a study of current patterns and changes in the riverbed before the 2018 Tsunami. The riverbed in the Palu Estuary changes simultaneously due to three factors: sediment supply from the upstream, flow intensity and tidal fluctuation. The recent increase in extreme discharge also plays a major role in influencing bed morphology. Lutfi [9], [10] and Sabhan [11] also conducted a study at the same site but did not analyze sediment transport [9], [10], [11]. Similar studies have also been carried out in other locations, such as: Pari et al. [12], Chen et al. [13], van Maren et al. [14] and many other researchers. This study is very interesting because it aims to identify the velocity and direction of transport due to changes in the bed morphology. The information from this paper can be used as a reference for studying bed morphology due to tsunami in other areas and specifically for managing the downstream section of the Palu River.

2. Materials and Methods

2.1 Study Area

Palu Estuary as the research location site is located at the southern tip of Palu Bay (Fig. 1). This area is the outlet of the Palu River, one of the largest rivers in Central Sulawesi which divides Palu City into two parts: West Palu and East Palu. The intensity of deposition at this point is very intensive due to the high sediment transport originating from Palu Watershed [15]-[17]. The currents followed by sediment transport from the sea due to tidal fluctuations also contribute to high sedimentation. Changes in the bed morphology due to the tsunami after the 2018 Palu Earthquake are likely to change the characteristics of sediment transport at this location.

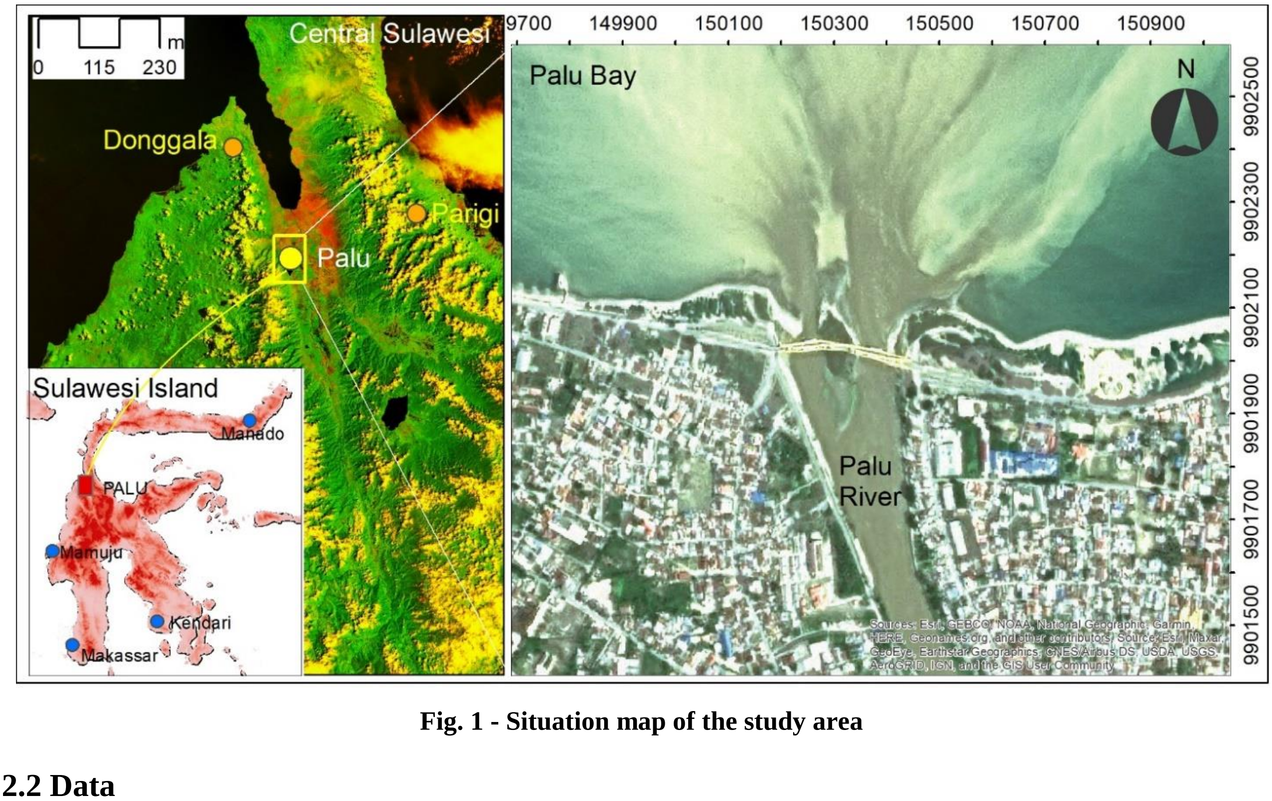

Fig. 1 - Situation map of the study area

2.2 Data

Apart from the bathymetry data after the 2018 Tsunami at the study location as the basis for the preparation of the 2D mesh, there are three main data that are applied as the input and boundary conditions. The input data is the bed sediment at the study location obtained from a survey in previous studies [7], where this data is dominated by fine sand. In the simulation, these data are expressed in terms of a grain gradation curve represented by a diameter corresponding to 50% passes (D50).

Boundary condition data includes three input data at the upstream boundary and one input data at the downstream boundary. The upstream boundary input consists of three discharge variations representing the minimum, average and maximum conditions. This data is a secondary type that is converted from the Automatic Water Level Recorder (AWLR) data using the rating curve equation. The latest data for downstream boundary input is tide data measured after the 2018 Tsunami.

2.3 Methods

The whole study was carried out by performing 2D hydrodynamic simulation using Surface-water Modeling System (SMS). The two main modules in this program package are RMA2 and SED2D, for modeling flow and sediment transport, respectively. Both modules are simulated in an unsteady state to accommodate tidal fluctuations at the downstream boundary. Three sets of simulations were executed with a combination of the discharge at the upstream boundary: low flowrate, average flowrate, and maximum flowrate. The numerical stability is evaluated by optimizing the mesh quality and simulation time [18]-[20].

The sediment transport formula in the SED2D module is the convection-diffusion equation as follows:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) + S \tag{1}$$

where C is the concentration of sediment, D_x and D_y are the coefficients of effective sediment diffusion in x and y directions. u and v are flow velocity in x and y directions, t = time, and S = the term of bed source quantifying the exchange of net sediment at the floor between the bed and the water body.

Eq. (1) is capable of calculating transport of both clay and sand by differentiating formulas on S. For sediment transport on the bed, S is expressed in the form:

$$S = \frac{C_{eq} - C}{t_c} \tag{2}$$

$$C_{eq} = \frac{\gamma_s D_{35} C_2 \left(\frac{F_{gr}}{C_3} - 1\right)^{C_4}}{H\left(\frac{u^*}{\bar{u}}\right)^{C_1}} \tag{3}$$

where C_{eq} = transport potential according to Ackers and White sediment transport equations [19], t_c = characteristic time, γ_s = unit weight of sediment, C_1, C_2, C_3 and C_4 are the parameter of Ackers and White, Ackers and White, D_{35} = effective diameter of sediment grain, F_{gr} = mobility index, u^* = bed shear velocity and $\bar{u}$ = average velocity of flow.

3. Results and Discussion

3.1 Estuary Situation After the Tsunami

The tsunami caused by the 2018 Palu Earthquake has resulted in major changes to the morphological bed in the estuary. There are three fundamental changes apart from the collapse of the Bridge of Palu 4 after the tsunami. First, the sediment deposited at the middle of river mouth was eroded by the tsunami waves which caused a decrease in the elevation of the riverbed (Fig. 2(a) and Fig. 2(b)). The riverbed drops and the flow depth at the same discharge and tide conditions increases. The mouth of the river is more vertically open than it was before the tsunami. Second, the intensity of the deposition outside the river mouth becomes more intensive compared to the results of the study performed by Madman [7]. The waterbed in this area has become shallower due to deposition of sediment from eroded river outlets. However, in fact the base elevation downstream of this outlet is deeper than the previous condition. This is probably related to the bed subsidence due to a large earthquake [21]. Finally, both sides of the outlet have been abraded by the tsunami. The outer boundaries of both sides of the outlet have shifted inland up to 30 meters and the coastline has changed.

3.2 Sediment Gradation

In general, sediment that is transported along the stream and settles before reaching the mouth of the river is included in the category of medium sand. The finer particles in the clay and silt groups generally settle downstream of the outlet, similar to that presented by Madman [7]. The deposition intensity tends to increase significantly when the sediment supply from upstream tributaries accumulates simultaneously. Ephemeral and intermittent tributaries that run out of the Palu River such as the Sombe-Lewara River, Rogo River, Bangga River, Paneki River, Kawatuna River, Poboya River and other similar rivers contribute greatly to sediment transport and deposition in the estuary.

Sieve analysis applied to three sediment samples revealed that the sediment size distribution was dominated by moderate to fine sand (Fig. 3). This grain size characterizes the distribution of transported sediment where the grain size decreases the closer to the estuary. The average of median diameter (D50) of the three samples was 0.822 mm.

(a) (b)

Fig. 2 - Situation of bed morphology in Palu Estuary (a) before before 2018 tsunami, and; (b) after 2018 tsunami

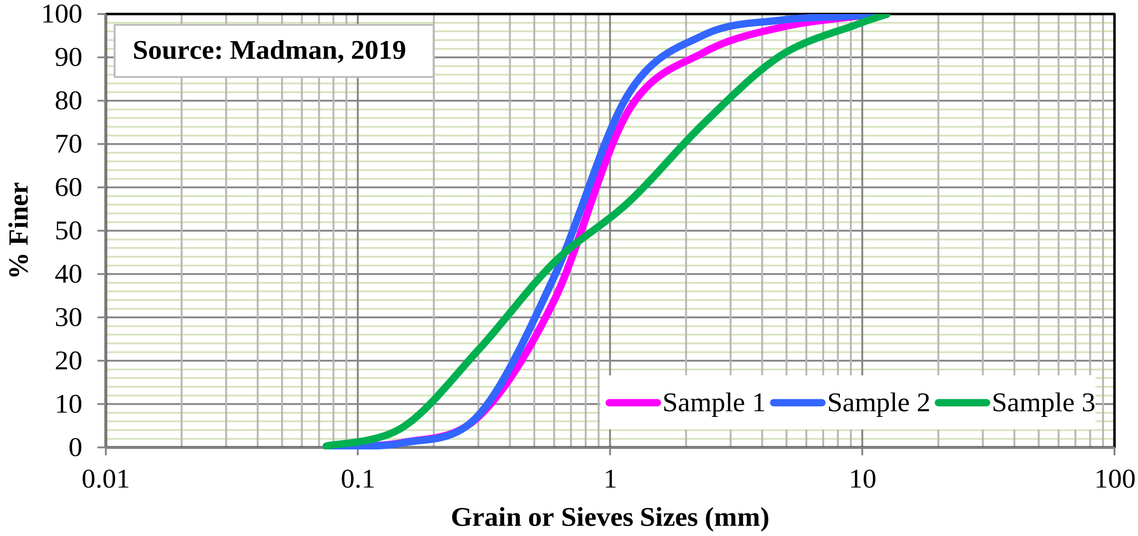

Fig. 3 - Grain sizes distribution of three sediment sample

3.3 Characteristics of Sediment Transport

Hydrodynamic simulations that have been performed in three conditions can describe fluctuations in velocity and direction of sediment transport. The velocity of sediment transport is related to the velocity of the flow that moves it. At the minimum discharge and low tide (Fig. 4(a)), the flow velocity tends to be normal, and the sediment grains can settle throughout the modeled domain. Larger grains of sediment gradually settle as the flow rate decreases before the tide level affects the flow from the river. The bed degradation after tsunami at the river mouth significantly affects the flow velocity in this condition.

The transport rate rises with increasing discharge where the peak of the transport is reached at the maximum and low tide discharge (Fig. 4(b)). In this condition there is almost no resistance to flow along the domain. Low tide combined with high discharge creates critical flow, in this condition the flow rate changes suddenly, and it is possible that all sediment grains will be transported and settle downstream of the river mouth. Likewise with high tide conditions. Sediment tends to settle in the backflow area at both low and high discharge (Fig. 4(c) and Fig. 4(d)). The reduction in flow velocity in this area is the result of high tide pressure resulting in backflow because the tide level is higher than the normal water level.

The current direction can be observed well under two conditions: low tide and high tide. In both these conditions the current moves in opposite directions. The current moves towards the river along with the rise of the tide level, on the other hand, with the decrease in the tide level the current will move towards the sea. The most important thing that can be inferred from this simulation is that the direction of the current after the tsunami is straighter than before. Changes in bed configuration and river mouth situation can affect the flow direction including the transport rate.

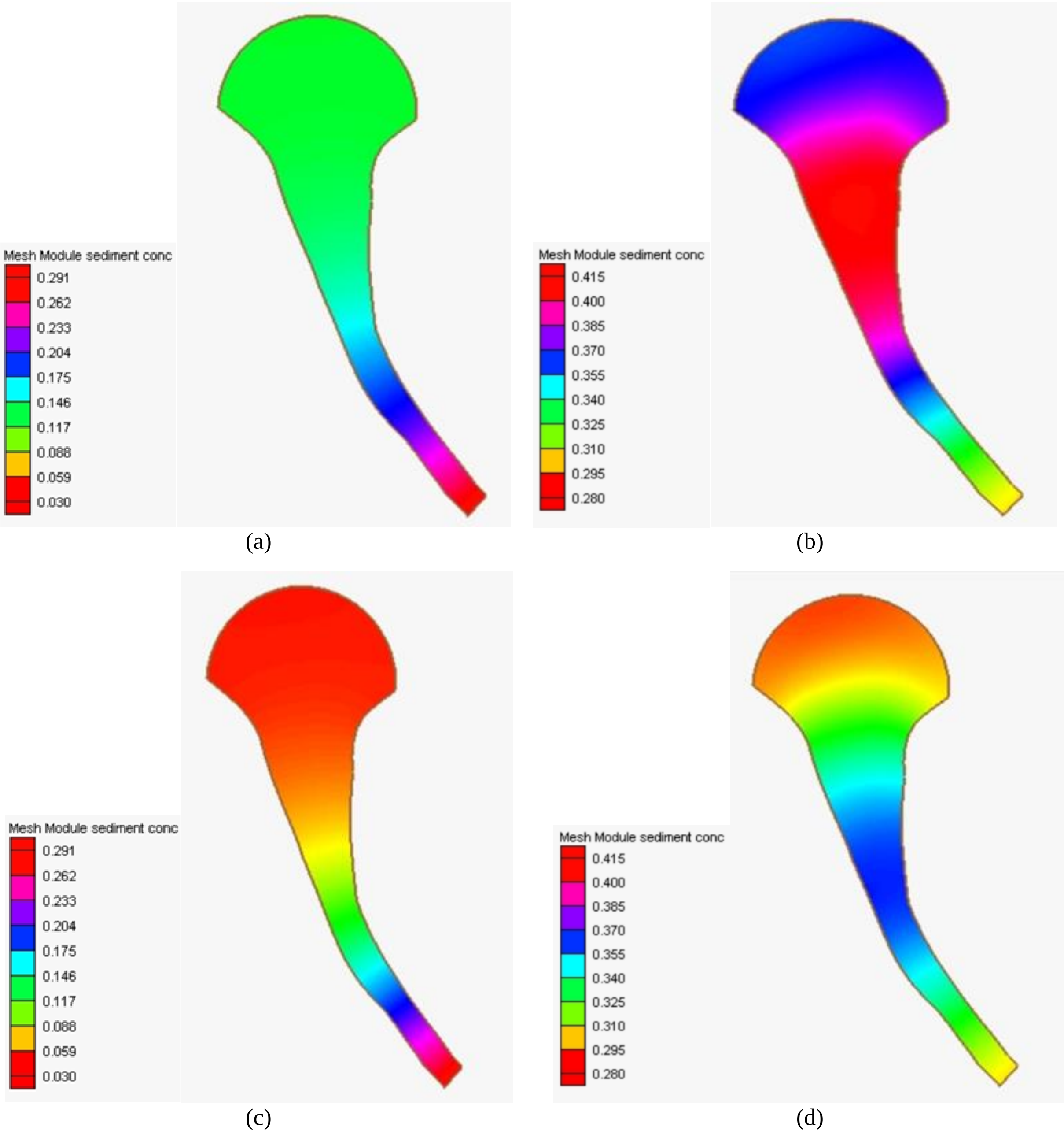

Fig. 4 - Sediment transport characteristics in the Palu Estuary at (a) minimum flow-low tide; (b) maximum flow-low tide; (c) minimum flow-high tide, and; (d) maximum flow-high tide

4. Conclusions

2D hydrodynamic simulations have been performed to assess the impact of bed morphological changes on sediment transport characteristics in the Palu Estuary after the 2018 Tsunami. The 2D mesh that defines the basic geometry is created from the bathymetry data surveyed after the tsunami. Three simulated transport sediment scenarios have been applied. Low discharge, average discharge, and maximum discharge as input of the upstream boundary and 15 daily tide time series at the downstream boundary.

The simulation results inform that the transport rate, velocity, and direction of sediment movement have slightly changed from the simulation results before the tsunami. At minimum discharge and high tide, almost all sediment settles upstream of the river mouth. Most of the sediment settles after leaving the mouth of the river at maximum discharge and low tide.

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