Numerical model of ocean currents, sediment transport, and geomorphology due to reclamation planning in Palu Bay

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Abstract. Reclamation in developing countries such as Indonesia is being intensely carried out, especially in cities that are located on the coast to create new residential locations; the Palu City as the provincial capital of Central Sulawesi is also planning reclamation activities. This research was conducted to see the changes in current, distribution of suspended sediments and the potential for abrasion and sedimentation by reclamation plans in Palu Bay. The model is a numerical model and it was constructed from continuity and momentum equations. Wind, tides, river discharge and atmospheric parameters were used for model input to generate current, wave and total suspended solid distribution. Before the construction of reclamation, the model showed that a strong current velocity in receding conditions leads to the tide reaches the coast to the east of the Palu River estuary, while in high tide conditions to recede, strong currents in the eastern part of the Palu River estuary move to north. The sediment dispersal from the mouth of the dominant river moves to the west of the Palu River estuary both before and after reclamation. The bottom waters experienced sedimentation and abrasion has been strengthened after this reclamation because the wave energy has not been weakened before crashing into the reclamation wall.
Key Words: current, suspended sediments, bathymetry changes, reclamation, Palu bay.

Introduction. Palu Bay as the capital city of Sulawesi province is experiencing rapid development so that it needs new areas as a means of tourism, trade and new settlements. The choice of new land can be obtained through the process of reclaiming the Palu bay. Reclamation activities affect quality of life such as the occurrence of flash floods and traffic congestion and health. The coastal reclamation process must consider the temporary and permanent negative impacts on the community (Nadzir et al 2014). Reclamation has a detrimental effect on the macrobenthic community and significantly alters the macrobenthos community structure, but may be useful for benthic infauna outside the reclamation area (Lu et al 2002). Changes in coastal bathymetry by reclamation can cause changes in current velocity in other areas affording damage to the residential environment (Malhadas et al 2009). Reclamation construction can cause serious erosion problems due to changes in current and wave (Franz et al 2017).

Research showed that reclamation of water bodies disrupts normal energy gradients, thus inhibiting sediment deposition (Flemming & Nyandwi 1994). Reclamation can reduce the speed of tidal currents by 10% (Manda & Matsuoka 2006). The long shore component of tidal currents intensifies currents towards the sea above the intertidal zone (Chambers et al 1991). Ecologically, reclamation can also eliminate places of life for

some species of birds due to the reduction of wetlands where they seek for food (Yang et al 2011; Yu et al 2017; Wu et al 2018). Reclamation provides the advantage of increasing fresh groundwater sources because reclaimed soil can be an additional aquifer and replenishment of rain occurs in a wider area (Chen & Jiao 2007; Guo & Jiao 2007).

Modeling changes in current, dispersion of suspended sediments and changes in sea depth are very important to see the possible effects of reclamation on both the coastal morphology and the survival of the biota affected by reclamation. Large-scale coastal reclamation causes: loss of wetlands in coastal areas, negative environmental impacts, and potential disasters caused by coastal flooding due to climate change (Tian et al 2016; Meng et al 2017). Research on sedimentation formation behind barrier islands due to Hurricane Ivan in Santa Rosa Island in Florida (Houser et al 2008), then research Van Dongeren developed models of flow, wave and sediment transport calculations, which led to morphology by dredging (Van Dongeren et al 2008). Related research was also carried out by Franz by modeling bathymetry changes due to waves and currents (Franz et al 2017). Previous research has not modeled morphology changes effect of reclamation.

This study hopes to provide input on the impact that will occur on morphological changes, cohesive sediment distribution and current velocity that will occur in case the coastal reclamation in Palu Bay will be granted, and provide the best solution for the security and sustainability of the ecosystem in the bay of Palu. Specifically, this study will compare the flow, distribution of dissolved solids and morphology changes before and after reclamation to see the impact of reclamation.

Material and Method

Data of input model. The data needed as a model input are tidal data, wind, river discharge and depth of the waters of Palu Bay. Tidal data is obtained from FES2004 prediction data consisting of 14 components (Table 1), while wind data obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) in the form of 3-hour wind data. River discharge data is the maximum value data from the monthly average in 2016, while the water depth data is obtained from Dishidros-AL. The dimension of the model uses a grid of 0.001x 0.001° d with a grid slope of 20°. The model is ran for 29 days started from January 2016.

Equation of model developed. MOHID 2016 was used to hydrodynamic model and modeling sedimentation changes. All models are run using the MOHID STUDIO 2016 software (Cancino & Neves 1999). Hydrodynamic modeling is modeled using a finite volume with the vertical coordinate type zigma. The model is constructed with the Navier-Stokes equation with the Boussinesq and hydrostatic approaches for continuity and momentum:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (1)$$

$$\partial u/\partial t + u\,\partial u/\partial x + v\,\partial u/\partial y + w\,\partial u/\partial z - fv = 1/\rho_0 \quad \partial p/\partial x + \partial/\partial x\,((\nu_H\ \partial u/\partial x) + \partial/\partial y\,((\nu_H\ \partial u/\partial y) + \partial/\partial z\,((\nu_t\ \partial u/\partial z) \qquad (2)$$

$$\partial v/\partial t + u\,\partial v/\partial x + v\,\partial v/\partial y + w\,\partial v/\partial z + fu = 1/\rho_0 \quad \partial p/\partial x + \partial/\partial x\,((\nu_H\ \partial v/\partial x) + \partial/\partial y\,((\nu_H\ \partial v/\partial y) + \partial/\partial z\,((\nu_t\ \partial v/\partial z) \qquad (3)$$

$$\frac{\partial p}{\partial z} = -\rho.g \qquad (4)$$

where: u, v and w are velocities in the direction x, y and z (m s^{-1});
   f is Coriolis parameter (rad s^{-1});
   νh and νt are coefficients turbulent viscosity horizontal and vertical (m^2 s^{-1});
   p is pressure (Pa);
   ρo is the reference density (kg m^{-3}).

Sediment transport is solved using the advection-diffusion flux equation. The equation can be written in the form (Cancino & Neves 1999):

$$\partial A/\partial t + \partial(uA)/\partial x + \partial(vA)/\partial x + \partial((w + w_s)A)/\partial z = \partial/\partial x\,((\varepsilon_x\ \partial A/\partial y) + \partial/\partial y\,((\varepsilon_y\ \partial A/\partial y) + \partial/\partial z\,((\varepsilon_z\ \partial A/\partial z) \qquad (5)$$

where: A is concentration of total suspended solid;
   t is time;
   x, y are horizontal coordinates, z is vertical coordinates;
   εx, εy, εz are the diffusion coefficient of the sediment mass;
   ws is velocity of the falling sediment;
   u, v, w are velocity of the flow in the direction x, y and z.

Erosion occurs when the ambient shear stress exceeds the erosion threshold. The eroded sediment flux is given by Cancino & Neves (1999):

$$\frac{\partial M_E}{\partial t} = E\left(\frac{\tau}{\tau_E} - 1\right) untuk \tau > \tau_E$$

$$\frac{\partial M_E}{\partial t} = 0 \quad untuk \tau < \tau_E$$

(6)

where: τ is bottom shear stress;
τ_E is the critical sliding measure for erosion;
E is erosion constituent ($kg\ m^{-2}\ s^{-1}$).

Deposition is calculated as the result of depositional flux and the possibility of particles to remain at the base (Cancino & Neves 1999):

$$\frac{\partial M_D}{\partial t} = C_B(W_s)\left(1 - \frac{\tau}{\tau_D}\right) untuk \tau > \tau_D$$

$$\frac{\partial M_D}{\partial t} = 0 \quad untuk \tau < \tau_D$$

(7)

where: τ_D is a critical voltage for deposition.

Data analysis. The current data from the measurement is analyzed by doing a low pass filter to eliminate effect of high-frequency wave ripple on the current. Current data of filter results are analyzed to separate the tidal and residual currents using Institute of Ocean Sciences (IOS) method (Foreman 1978).

Table 1

Tidal Harmonic Components used in the model

No	Symbol	Name of components
1	M2	Principal lunar semidiurnal constituent
2	S2	Principal solar semidiurnal constituent
3	K1	Lunar diurnal constituent
4	K2	Lunisolar semidiurnal constituent
5	N2	Larger lunar elliptic semidiurnal constituent
6	2N2	Lunar elliptical semidiurnal second-order constituent
7	O1	Principal lunar diurnal
8	Q1	Larger lunar elliptic diurnal constituent
9	P1	Solar diurnal constituent
10	M4	Shallow water overtides of principal lunar constituent
11	Mf	Lunisolar fortnightly constituent
12	Mm	Lunar monthly constituent
13	Mtm	Long period termensual
14	MSqm	Long term constituent

Results and Discussion

Validation model. The results of the tidal validation of the model measurements by Geospatial Information Agency (BIG) for 30 days from 1 to 29 January 2016 showed that the corresponding tidal type in the study location was the type of double tidal mix (Figure 1A). The plot results between the tide of the blue line model and the measurement results (BIG data) of the red line indicated the same trend. It means that the tidal model results represent the real tidal condition at the research location. Current validation (Figure 1B) by comparing the results of the model and the measurement results for 3 days showed that the model results represented by the red dot which was the zonal

scatter velocity versus the meridional velocity showed that the average zonal (west east) current velocity was greater compared with meridional current velocity (north south). The results of the measurement data showed that the same trend with the results of the model with a minor ellipse axis that is greater than the minor ellipse axis results from the model. Meridional velocity of the measurement results is greater than the results of the model because does not accommodate all parameters in nature that generate currents. But as a whole the current direction trend between models and measurements shows good conformity so that the model is considered to represent the environmental conditions. But as a whole the current direction trend between models and measurements shows good conformity so that the model is considered to represent the environmental conditions.
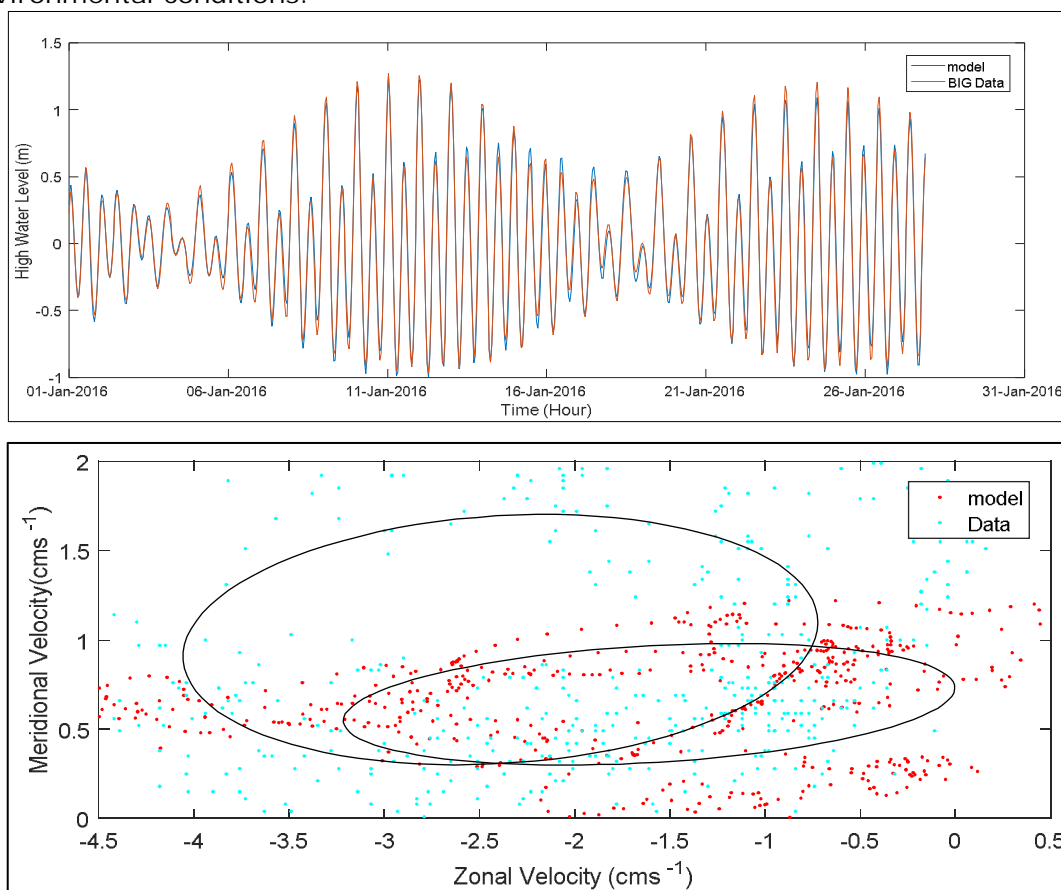

Figure 1. A (above) - level of water of model results and measurement data; B (below) - velocity of measurement data results and model results.

Current velocity model. The model results indicated that reclamation activity increases the maximum current velocity in the model domain from 0.8 to 1.45 cm s^{-1} and increase sedimentation from 1.62 to 1.99 cm and abrasion from -0.16 to -0.29 cm respectively during the simulation period (Table 2).

Table 2

Summary of model results

No	Ctegory	Max value	Min value
1	Current velocity before reclamtiaon	0.8 cm s^{-1}	0 cm s^{-1}
2	Current velocity after reclamtiaon	1.45 cm s^{-1}	0 cm s^{-1}
3	Change of bathymetry before reclamation	1.62 cm	-0.16 cm
4	Change of bathymetry after reclamation	1.99 cm	-0.29 cm

(-) is abration.

The current velocity at the highest tide shows that the currents in the west bay move south while in the eastern part of the bay moves north with a weakening current velocity after entering the bay with a higher depth after reclamation (Figure 2A). The direction of the current before reclamation is the same as after reclamation but the velocity of the current after reclamation is higher by narrowing of geometry (Figure 2B). The current pattern at low tide to the tide shows a pattern of currents that move to the south in the west of the bay and to the north in the east of the bay, the strengthening of currents to the north in the western part is caused by ocean currents added by the Palu River flow (Figure 3A), the eddy formed which strengthened after reclamation (Figure 3B), this eddy was formed by the confluence of ocean currents with the flow of the Palu river.

Figure 2. Current velocity lead up high tide: A (left) - after reclamation; B (right) - before reclamation.

Figure 3. Current velocity at low tide to tide: A (left) - after reclamation; B (right) - before reclamation.

Cohesive sediment and morphology. The distribution of cohesive sediment after reclamation (Figure 4A) and before reclamation (Figure 4B) are simulated originating from the Palu River with a concentration of 10 mg L^{-1} with a river discharge of 60 m^3 s^{-1}. The results of the model show that after reclamation the distribution of cohesive sediment with higher concentrations affects the area further from the mouth of the river, this is caused by constringency flow by reclamation. After passing through the reclamation area the distribution pattern of cohesive sediment has the same pattern before and after reclamation.

Change in morphology of model results throughout the simulation period after reclamation (Figure 5A) and natural or no reclamation conditions (Figure 5B). The results of this model are simulated with the assumption of uniform base sediment (D50), with the force factor causing changes in bathymetry are waves and currents that work simultaneously. Before reclamation, changes in bathymetry were mostly concentrated in the west of the Palu river estuary in the form of sedimentation, while in the eastern part of the estuary of the Palu, bathymetry changes in the form of abrasion (value (-)). While the conditions after reclamation of bathymetry changes occurred in front of the reclamation site in the western part of the Palu River estuary, different things were obtained after reclamation where sedimentation occurred in the northern part of the reclamation site on the east coast of Palu Bay.
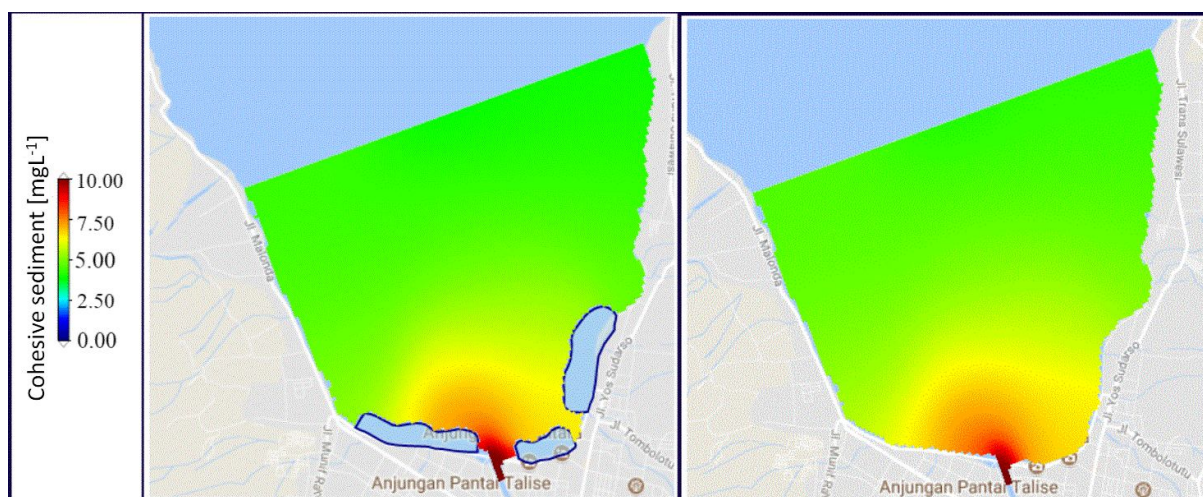
Figure 4. Cohesive sediment: A (left) - after reclamation; B (right) - before reclamation.
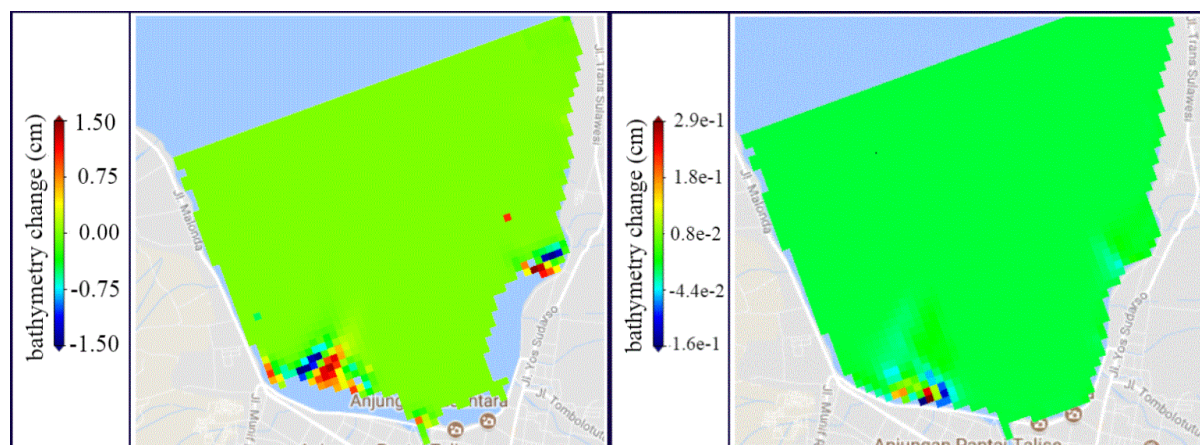

Figure 5. Changing bathymetry: A (left) - after reclamation; B (right) - before reclamation.

Discussion. The results of the model showed that the type of tidal in the Palu Bay is a mix semidiurnal cycles of tidal with a tidal range of 2.25 m (Figure 1A). This tidal type corresponds to the results of the study (Wyrtki 1961) in the Makassar Strait. The results of the model with measurement data for water level and current velocity showed a good compatibility (Figure 1B), so that the produced model is considered to represent environmental conditions.

The current velocity lead to highest tide increases on the west side of Palu Bay which moves from south to north, and the formation of a eddy due to the movement of the current moving out is related to the quite large Palu River discharge (Figure 2B). The current speed reaches 0.8 m s^{-1}. Conditions changed after reclamation (Figure 2B) where there was a narrowing of the canal which caused a strengthening of the current to the

north. Eddy is formed by the confluence of river currents and tidal currents according to those found in Lasolo Bay in Southeast Sulawesi (Surinati & Kusmanto 2016).

Suspended sediment distribution which is simulated as a result of the Palu River with a concentration of 10 mg L^{-1} will spread to the north with a distance of 2 km to reduce the concentration to 5 mg L^{-1} (Figure 4), with a higher concentration to the west of the Palu River estuary follow the dominant current velocity pattern (Atmodjo 2011).

Morphology changes are modeled with a wave generator that simulates in 10 days assuming the type of sediment of all waters is the same. Sedimentation and abrasion patterns before and after reclamation (Figure 5) showed that before reclamation there was sedimentation with a thickness of 0.29 cm and 0.16 cm abrasion. A dominant abrasion occurs in the western part of the bay and partly in the east while sedimentation occurs on the western edge of the Palu Bay. Abrasion occurs due to increased turbidity and sedimentation as the flow velocity decreases (Mulder et al 1998).

The planned reclamation will cause intensification of abrasion to 1.62 cm and sedimentation of 1.99 cm. Abrasion and sedimentation occur both to the west and east of the edge of the Palu bay which borders the reclamation wall threatens the reclamation wall, reclamation has a moderate impact on changes in bathymetry (Mostafa 2012). Strong abrasion corresponds to locations where significant high wave heights (not shown in this paper). Significant wave height cause a mixture of the sedimentary bottom layer which then carries the sediment along the coast until conditions of weak coastal shear current and sediment undergo sedimentation (Kamphuis 1991).

From the description it is recommended to avoid the construction of reclamation because it increases the speed of flow and changes in bathymetry, which is worried about being dangerous especially if a tsunami occurs as happened on 28 September 2018 which is right in Palu Bay. If reclamation is done then the reclamation edge that leads to the sea needs to be planted with trees so that it becomes a natural barrier to high waves such as tsunami waves.

Conclusions. From the results of the model, it can be seen that the presence of reclamation causes a narrowing of the eddy so that the current velocity is increased from 0.8 to 1.45 m s^{-1}. Whereas the distribution of suspended sediments did not change much with the reclamation. Reclamation will cause intensification of abrasion to 1.62 cm and sedimentation of 1.99 cm from previous sedimentation of 0.29 cm and abrasion of 0.16 cm.

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