Numerical Modeling of Sediment Transport in a River Mouth

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1. Introduction

The Lamong River is located in East Java Province, Indonesia. According to its administrative territory, the upstream portion of Lamong River is flows through Lamongan and Mojokerto Regencies, the downstream portion flows along the border between Gresik Regency and Surabaya City before flowing into the Madura Strait. The river mouth coordinates on Universal Transverse Mercator (UTM) is 683537.456, 9204569.552. The Lamong Watershed has an area of approximately 720km^2 and 103km river length with seven tributaries. In the estuary, the stream separates into two directions that form an island in the middle. The Lamong Estuary is considered as the tidal flat area, it means that during the spring-neap cycle the estuary is covered by water during flood tide and as open land by ebb tide. This condition is considered to be one of the causes of inhibited river flow to the sea, which is led to settlement of transported sediment. The influence of surrounding rivers such as the Semeni, Branjangan, Manukan, and Krembangan Rivers could increase the capacity of sediment transport into the Lamong Estuary. Madura Strait with Lamong Estuary as one of its ecosystem is a part of sea traffic in the eastern region of Indonesia, it is also considered as the factor which has responsibility to backwater that cause floods in Surabaya City. The rapid development in the Surabaya region as a center of eastern region development of Indonesia has resulted in the escalation of Lamong region value due to its position among sea-traffic, domestic interest, and military facilities. Therefore, sediment transport analysis in the Lamong Estuary is needed for the reason above. The Coastal Modeling System (CMS) is an integrated numerical modeling system for simulating nearshore waves, currents, water levels, sediment transport, and morphological changes (1). The CMS includes a flow model which calculates hydrodynamic and sediment transport in CMS-Flow and a wave model in CMS-Wave. At the first stage of this simulation is by investigating hydrodynamics of tides and tidal flow in this area to get validated simulation by calibrate the simulated tide sea water level with observed water level.

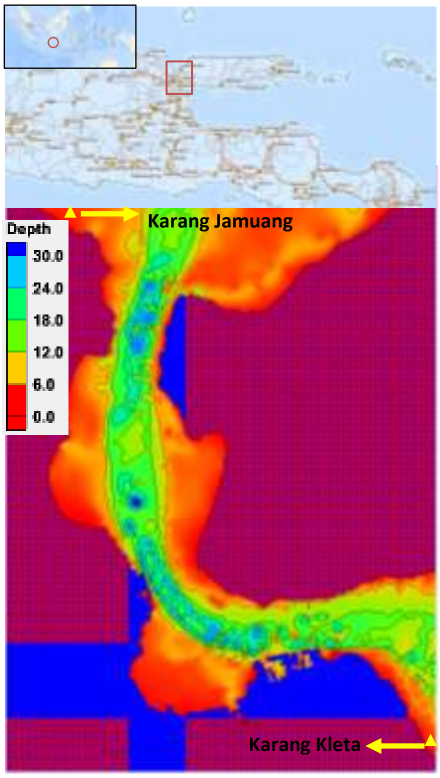

Figure 1. Study location and computational grid with initial bathymetry for 2009. Square cells represent inactive land cells.

2. Concept and Method

As stated above, there are two models within the CMS system, CMS-Flow and CMS-Wave. CMS-Flow is a two-dimensional (2D) depth-averaged nearshore circulation model, sediment are simulated as a passive scalar and assumed to be non-cohesive, and have constant density and porosity (2). CMS-Flow calculates currents and water levels including physical processes such as advection, turbulent mixing, combined wave-current bottom friction; wind, wave, river, and tidal forcing; Coriolis force; and the influence of coastal structures. CMS-Wave is a spectral wave transformation model and solves the wave-action balance action using a forward-marching finite difference method. CMS-Wave includes physical processes such as wave shoaling, refraction, diffraction, reflection, wave-current interactions, wave breaking, wind wave generation, white capping of waves, and the influences of coastal structures (3). The benefit of using this system is CMS-Flow and CMS-Wave can be run separately or coupled together using steering procedure. Based on the above definitions, hydrodynamic mathematical formulations used in this model can be expressed as:

$$\frac{\partial(hV_i)}{\partial t}+\frac{\partial(hV_jV_i)}{\partial x_j}-\varepsilon_{ij} f_c hV_j=-gh\frac{\partial\bar{\eta}}{\partial x_i}-\frac{h}{\rho}\frac{\partial p_{atm}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(v_t h\frac{\partial V_i}{\partial x_j}\right)-\frac{1}{\rho}\frac{\partial}{\partial x_j}\left(S_{ij}+R_{ij-}\rho hU_{wi}U_{wj}\right)+\frac{\tau_{si}}{\rho}-\frac{\tau_{bi}}{\rho} \qquad (1)$$

where t is the time, x_i is Cartesian coordinate in the jth direction, f_c is coriolis parameter, h is wave-averaged total water depth, $\bar{\eta}$ is wave-averaged water surface elevation with respect to reference datum, S_M is water source/ sink term due to precipitation, evaporation, and structures, V_i is total flux velocity, U_i is wave and depth-averaged current velocity, U_{wi} is mean wave mass flux velocity or wave flux velocity for short, g is gravitational constant, p_{atm} is atmospheric pressure, ρ_{atm} is atmospheric pressure, ρ is water density, ν_t is turbulent eddy viscosity, τ_{si} is wind surface stress, S_{ii} is wave radiation stress, R_{ii} is surface roller stress, and τ_{bi} is combined wave and current mean bed shear stress. The modeling approach for sediment transport is using non-equilibrium transport model (4).This means to get more realistic result by using Lund-CIRP formula. This formula does well in predicting the surf zone sediment transport but tends to overestimate the transport rates near the wetting drying limit and in deep water (> 10m). The current-related bed and suspended-load transport with wave stirring are given by:

$$\frac{q_{b*}}{\sqrt{(s-1)gd_{50}^{3}}} = f_b \rho_s 12\sqrt{\Theta_c}\,\Theta_{cw,m} \exp\left(-4.5\frac{\Theta_{cr}}{\Theta_{cw}}\right) \quad (2) \qquad \frac{q_{s*}}{\sqrt{(s-1)gd_{50}^{3}}} = f_s \rho_s c_R U \frac{\varepsilon}{\omega_s}\left[1-\exp\left(-\frac{\omega_s h}{\varepsilon}\right)\right] \quad (3)$$

where q_{b*} is equilibrium bed load transport, q_{s*} is suspended load transport, d_{50} is median grain size, s is the sediment specific gravity or relative density, g is gravitational constant, ρ_s is sediment density, Θ_c is shields parameters due to currents, $\Theta_{cw,m}$ is mean shields parameters due to waves and currents, Θ_{cr} is critical shields parameter, ε is vertical sediment diffusivity, c_R is reference bed concentration, f_b is bed-load scaling factor, and f_s is suspended-load scaling factor.

3. The Physical Condition in the Lamong Estuary

As stated in the Introduction, the shallowing processes in Lamong Estuary occur in complex way. The estuary is situated in the west-to-east direction, and it connects with the Lamong River on the west end and with the Madura Strait on the east end. Based on the morphology of the river, the downstream part flows in the alluvial plain with a slightly steep slope. It causes the sediment that is transported by the river to consist predominately of the finer particles. It is a mixed-energy, tide-dominated estuary. The tide at Karang Jamuang Station is diurnal with an average spring tidal range 0.6 m and at Karang Kleta Station is semidiurnal with an average spring tidal range of 2.5 m. Downstream, the Lamong River separates into two directions, i.e., north and south, forming an island between them that is named as Pulau Galang. Based on East Java Province's regional regulations, this island is designed as a conservation area. During low tide the area surrounding the Pulau Galang is exposed as open land approximately as far as 400m offshore.

4. Result and Discussion

The simulation was prepared as a non-linear grid type with resolutions of 150 m x 150 m offshore and 10 m x 10 m in the inlet area of the Lamong River and four selected rivers surrounding it, total grid for flow computation that consisted 152,588 cells. Computational grid domain covers an area of 21860 m x 30933 m. By means of harmonic analysis, the water levels at the two open sea boundaries were determined to simulate the tidal flows over a period of time. The Lamong River and the other four rivers surrounding it was set as flow-rate forcing as constant flow with one year return period. The bathymetry model was generated by combination of Lingkungan Pantai Indonesia (LPI) bathymetry map and General Bathymetric Chart of the Oceans (GEBCO) satellite remote sensing data. In Figure 3. and Figure 4. shows simulation result graph of current velocity and flow rate in karang kleta and karang jamuang observation station.

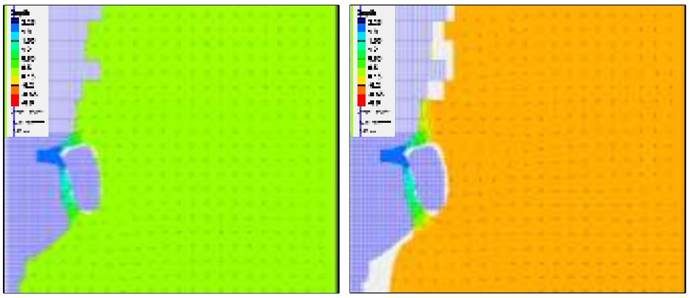

Figure 3. Hydrodynamic simulation visualization in Lamong Estuary. Left figure shows flood-tide velocity vector and water surface elevation. The ebb-tide hydrodynamic shows at the right figure

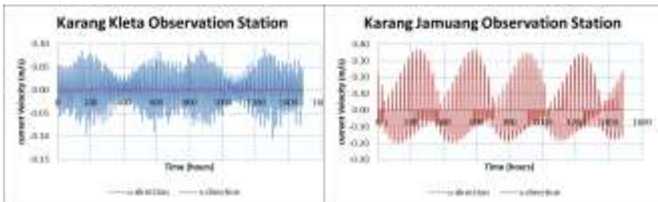

Figure 2. Current velocity value in observation station

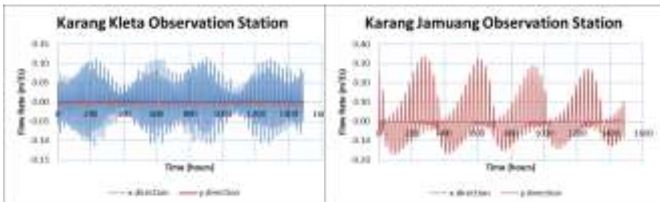

Figure 4. Flow rate value in observation station

5. Summary

The results shown in the graph indicate that by modeling the input as tidal-forcing and constant flow during following simulation time, the tidal current and tidal flow can be determined. From simulation for 2 months it is known that current velocity in karang kleta station is 0.0215m/s and 0.1054m/s in karang jamuang station and for the flow rate in karang kleta is 0.0325m^3/s and 0.0641m^3/s in karang jamuang. Based on this result further more analysis can be conducted to obtain the results morphological change due to sediment transport in the Lamong Estuary. The model will be coupled with a depth-averaged circulation model and a spectral wave transformation model.

References

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