Mangrove density impacts on tidal dynamic in Segara Anakan Lagoon, Indonesia

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Abstract. The present study aims to understand the tidal dynamics in a tropical coastal lagoon, Segara Anakan, Java, Indonesia. It is a shallow lagoon, with complex tidal channels and connected to the Indian Ocean by two channel outlets. It covers an overall area of about 12,000 ha. Three-quarters of the lagoons area have mangroves and the remaining quarter is covered by water. The Delft3D model has been implemented and validated using observation data. Scenario with uniform and spatially bottom drag coefficient were created in order to investigate the influence of the mangrove density on tidal dynamics. Based on tidal harmonic analysis, the M2 amplitude attenuates from both the western and the eastern lagoon inlets to the interior of the lagoon as the tidal wave is constricted by the narrow lagoon inlet and shallowness of the lagoon. For the case of uniform mangrove density, tidal harmonic analysis reveals M2 amplitude decreasing of 0.5 to 0.25 m from lagoon inlets toward central lagoon due to bottom friction effect. The tidal propagation into lagoon show increasing M2 tidal phase with maximum delay of 2.5 hours at the central lagoon. For the case of spatially mangrove density, the dampening of the tidal wave is stronger of 18% and the phase delay is longer 0.8 hours compare to the case of uniform mangrove density.

1. Introduction
Lagoons are highly productive ecosystems located at the transition between land and sea [1]. They are of ecological and economic importance to communities. These natural advantages led to the development of lagoon based on variety activities: industrial, commercial, and recreational [2]. Unfortunately, due to high development pressures on the land surrounding the lagoons often have led to increased sedimentation, eutrophication, water contamination, introduction of invasive species, and habitat destruction [3, 4, 5, 6, 7]. The end result is usually degraded water quality and decreased productivity of the lagoon [8]. These are particularly serious threats for the coastal regions of tropical Asia, which have been extensively modified by human activities as a consequence of rapid economic development and population growth [9].

Segara Anakan Lagoon (SAL) is located at the southern coast of Central Java, Indonesia. It is mangrove–fringed shallow coastal lagoon. The lagoon area has richness and diversity in living natural resources [10, 11, 12, 13] and play as a major ecological function to support a large and productive mangrove ecosystem. This ecosystem serves as a protective habitat for spawning, and represents nursery and feeding grounds for several aquatic organisms such as fish, crustacean and shellfish, including many commercial species [11]. Despite SAL importance, few studies on hydrodynamics have been carried out in this area: [10] reported an overview on hydrology, tides and currents of western SAL. Twenty years later, [14] provided first comprehensive hydrodynamics study in the
lagoon using analyzed observed data and a three-dimensional numerical model. Their results presented the effect of Citanduy River discharge on spatial distribution of salinity and water exchange between the eastern and western part of Segara Anakan. So far there is little quantitative information on tidal dynamics in the SAL. In particular, the effects of mangrove density on tidal dynamic are unclear but of high relevance for the accumulation of nutrients, pollutants and sediment in the lagoon.

Figure 1. Study area of Segara Anakan Lagoon. Field data station for water level at Klaces and Seleko. The inset panel displays a map of Indonesia and the position of the Segara Anakan Lagoon.

2. Study area
The Segara Anakan Lagoon (SAL) is situated at the southern coast of Central Java, Indonesia (Figure 1). SAL is a shallow estuarine lagoon with an average depth of 2.5 m. The lagoon is connected to the Indian Ocean by two narrow channel inlets. The width of the western inlet is 1 km, water depths range from 5 to 10 m. The eastern inlet is 1.25 km wide and has a water depth of 10–15 m. The hydrodynamic conditions are mainly influenced by tides and river discharge. The tide is predominantly semidiurnal with a variation of tidal range from 0.4 m during neap tides to 1.4 m during spring tides [14]. The lagoon receives its major freshwater input from the Citanduy River and some small tributaries. The climate of the region is dominated by monsoons. The wet NW monsoon brings heavy precipitation during austral summer (November–March) while the SE monsoon brings drier and cooler air masses during austral winter with the driest months being July–September [15]. The Citanduy River discharge varies between 78 and 294 m$^3$s$^{-1}$ (monthly average in period 1992 to 2008). On average, river discharge is 107 m$^3$s$^{-1}$ in the dry season and 268 m$^3$s$^{-1}$ in the wet season and it can rise to 550 m$^3$s$^{-1}$ in extremely wet years. Seasonal variability of freshwater input and sea water entry are responsible for seasonal changes of salinity in the lagoon. In the eastern lagoon, salinity averages 32 psu in the dry season and 27 psu in the rainy season, whereas average values in the western area are 21 psu and 10 psu, respectively [14].

3. Methodology
We use the numerical modelling system Delft3D-FLOW by Deltares [16] for the simulation of hydrodynamics in the SAL. The numerical model solves the Reynolds averaged Navier Stokes equations under the shallow water and the Boussinesq assumptions. Spatial discretization is done in a structured grid. For the spatial discretization of the advection terms, a combination of a third-order upwind scheme in the horizontal direction and a second-order central scheme in the vertical is used. For time discretization, an alternate direction implicit scheme is employed. The model equations and the detailed model descriptions are provided in [16].

The SAL is discretized by a rectangular grid with a horizontal spatial resolution of 40 m, covering a domain of 29.44 km in the east–west direction and 14.4 km in the north–south direction. The
bathymetry was derived from hydrographic charts and the bathymetric survey data conducted in 2005 and 2006 by [14]. The model is forced by the water levels and river flows at the lateral open boundary conditions. The water level variations are forced at its two open boundaries by eight major tidal constituents: four diurnal tidal constituents (Q1, O1, P1, K1) and four semidiurnal tidal constituents (N2, M2, S2, and K2), obtained from the Global Inverse Tide Model [17]. A constant river discharge is prescribed for the Citanduy River and various smaller distributaries. In the present study, the model simulate the two experiments: Experiment 1 uses a uniform Chezy roughness coefficient of $C_z = 50$ m$^{0.5}$ s$^{-1}$ and Experiment 2 uses the spatial bottom drag coefficient based on mangrove density as shown in Figure 2.

![Figure 2. Zonation map of mangrove density in Segara Anakan Lagoon observed by [13] and Manning coefficient value for *Rhizophora* according to [18]](image)

Figure 3. Results of model for water level with different Chezy coefficient scenarios at Seleko station (a). Comparison between modelled and observed for water level at Klaces (b) and Seleko station (c).
4. Results and discussions

4.1. Model validation

The model skill was evaluated by the Root Mean Square Error (RMSE) and a Skill Score (SS). The SS was calculated using the statistical method developed by [19] and further applied by [20, 21], defined as:

$$SS = 1 - \frac{\sum_{i=1}^{N}(X_{\text{mod}} - X_{\text{obs}})^2}{\sum_{i=1}^{N}(X_{\text{obs}} - \bar{X}_{\text{obs}})^2}$$

where $X$ is the variable being compared and $N$ is the number of measurements. When the model exactly agrees with the observations, SS equals 1; an SS of 0 means that the model provides equal predictive skill as the mean of the observations, and a negative SS represents that the model is less predictive than the mean of the observations. Performance levels are categorized by SS > 0.65 as excellent, 0.50–0.65 as very good, 0.2–0.5 as good, and < 0.2 as poor [20]. Water level data at Seleko show no significant effect of the variation of bed roughness (Chezy coefficient ($C_z$)) in the range of commonly applied values in similar environments (Figure 3). The simulations and observations for water elevation display good agreement at Seleko and Klaces (Figure 3), which is shown by the RMSE is 8.73 cm and 9.52 cm, while the SS is 0.61 and 0.53 (“very good”) for Seleko and Klaces, respectively.

4.2. Tidal wave propagation pattern

To investigate the tidal wave characteristics in the lagoon water levels were analyzed using the tidal harmonic analysis package $T_$TIDE [22]. Since the predominant tides in SAL is semidiurnal, thus in this study we only present the $M_2$ tidal constituent. The $M_2$ amplitude attenuates from both the western and the eastern lagoon inlets to the interior of the lagoon as the tidal wave is constricted by the narrow lagoon inlet and shallowness of the lagoon (Figure 4). From the west inlet toward the central lagoon, the narrow and complex morphology of the inlet dampens the $M_2$ amplitude from 0.5 m to 0.25 m. In the eastern lagoon the wide and deep channels gradually influence the $M_2$ amplitude which slowly decreases. The damping of tidal amplitude in the middle of the lagoon is occurred because the depth in the middle of the lagoon is shallower than at the inlets, thus the bed shear stress is significant dominant in the middle of the lagoon.

![Figure 4. M2 co–amplitude pattern in SAL for Experiment 1 (uniform bottom drag coefficient).](image-url)
The propagating tidal wave into lagoon experiences increasing in tidal phase lag due to bottom friction. The tides propagate through the inlets into the lagoon presenting different characteristic in western and eastern of the lagoon (Figure 5). The deep channels of the lagoon inlets display a small phase lag. By contrast, the shallower depth of middle lagoon causes stronger phase delay. Tidal harmonic analysis shows maximum $M2$ tide phase delay of 98.76 degrees (3.4 hours) in the central part of lagoon. The travel time for tides propagate from the west inlet to the central lagoon is 2.28 hours and from the east inlet to the central lagoon is 2.25 hours. These results indicate that tidal wave propagation from East Plawangan faster than the tidal wave from West Plawangan.

The $M2$ tidal amplitude decreases from the inlet towards the central zone of the lagoon by 50%. This dampening of the tidal wave is due to bottom friction caused by the shallow morphology of the lagoon [23]. [24] classifies that the tidal dynamics are modified by friction if $\zeta > \frac{H}{10}$, where $\zeta$ is the tidal elevation amplitude at the inlet and $H$ is the mean depth. For SAL, the tidal amplitude in the inlet is 0.5 m and $\frac{H}{10}$ of the average depth is 0.25 m. Therefore, the tidal hydrodynamics of SAL is modified by friction. [25] have shown before similar characteristics for an idealized estuary with two inlets. For example, the Terminos Lagoon with two inlets in which the tidal range decreases by 16% compared to the East inlet and 23% relative to the West inlet [26]. The attenuation of the tidal wave in Terminos Lagoon is lower compared to SAL, which is related to the more complex geometry of SAL. The lower tidal range in the central lagoon and the loss of energy leads to a lower tidal mixing and weaker residual currents.

4.3. The effect of mangrove density on tidal wave propagation pattern

The effect of mangrove density on tidal wave propagation in SAL is investigated using varies spatial bed friction. This varies spatial bed friction is represented by the zonation of mangrove density in SAL based on [13] (see Figure 2). Figure 6 displays the results of $M2$ co–amplitude pattern for the zonation of mangrove density (Experiment 2). The $M2$ amplitude is decreasing from 0.5 m to 0.16 m (the station A to the station D). The damping of $M2$ amplitude is also similar in the eastern lagoon (from the station I to the station D). By comparing to Experiment 1, decreasing of the tidal amplitude for Experiment 2 is stronger of 18%. This result confirms that the mangrove density has significant influence on reducing tidal amplitude due to increasing the bed friction.
Figure 6. M2 co–amplitude pattern in SAL for Experiment 2 (spatial bottom drag coefficient based on mangrove density zonation).

Figure 7. M2 co–phase pattern in SAL for Experiment 2 (spatial bottom drag coefficient based on mangrove density zonation).

Figure 7 displays M2 co–phase pattern for the three zonation of mangrove density scenario (Experiment 2). The M2 phase lag from the station A and D (western lagoon) and from the station I to D (eastern lagoon) are 94.83 degrees (3.18 hours) and 89.89 degrees (3.10 hours), respectively. By comparing the M2 phase lag from Experiment 1 and 2, the M2 phase lag resulted from the scenario the zonation of mangrove density is longer of 0.9 hours (54 minutes) than the uniform of mangrove density.

5. Conclusions
The tidal wave is propagating from both inlets toward the middle of the lagoon with decreased the tidal amplitude and increased the tidal phase. The tidal wave propagation from east inlet toward middle lagoon is faster compared to the tidal wave from west inlet toward middle lagoon. The mangrove density has significant effect on the tidal dynamics. This shown by decreasing of the M2
The tidal amplitude of Experiment 2 is 18% stronger than Experiment 1, while the M2 tidal phase lag of Experiment 2 is longer by 0.9 hours than Experiment 1.

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