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Tide and Tidal Current in the Mahakam Estuary, East Kalimantan, Indonesia

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Abstract Two-dimensional barotropic hydrodynamical model ECOMSED (Estuarine Coastal and Ocean Modeling System with Sediment) developed by HydroQual, Inc., (2002) has been applied to the Estuary of Mahakam Delta, East Kalimantan, Indonesia, to study the dynamics of tide and tidal current in this region. The model was run for 15 days (27 June–12 July 2003) using river discharge and tides as generating forces. The calculated elevation and current velocity agree well with the observed elevation (maximum amplitude of about 0.6 m) and currents velocity (maximum amplitude of about 0.15 m s^{-1}) in the Mahakam Estuary. The root mean squared error in the model elevation and current velocity are 0.15 m and 0.05 m s^{-1}, respectively. Wave form is changed from the mouth of the estuary to upstream. The natural oscillation period of the Mahakam Delta T_n is 19 hrs. T_n is near the period of diurnal tide and far from that of semi-diurnal tide. The decrease of semi-diurnal M_2, and S_2 amplitudes in the estuary is larger than that of diurnal (K_1, O_1) ones. The M_4 tidal current amplitude follows the M_2 tidal amplitude distribution, peaking at mid estuary, whereas M_4 tidal elevation amplitude is greatest farther to upstream. In the Mahakam estuary, tidal elevation amplitude distortion (M_4/M_2) is less than 0.3. For current amplitude, M_4/M_2 reaches a maximum of 1.85 about 40 km from the head of the estuary. The simulation results of the hydrodynamical model show that at flood condition and highest water, the waters flow into the delta, while at ebb condition and lowest water, it flows toward the Makassar Strait.

Key words: numerical model, tide, tidal current, Estuary of Mahakam Delta, river discharge

Introduction

The Mahakam Delta, located on the east coast of Kalimantan, Indonesia, is an active delta system which has been formed in humid tropical environment under condition of relatively large tidal amplitude, low wave-energy, and large fluvial input (Fig. 1(a)). Tidal processes control the sediment distribution in the delta mouth and are responsible for the flaring estuarine-type inlets and numerous tidal flats. The Mahakam estuary is influenced by tides and tidal currents from the Makassar Strait. The tides in the Makassar Strait are semi-diurnal with a considerable diurnal inequality. Tidal amplitude ranges from less than 0.2 m during the neap tide to about 0.6 m during the spring tide, which occur with a 15-day periodicity (Allen and Chambers 1998). Although such tidal amplitudes are not very large, they are sufficient to generate strong tidal currents which lead to reversing the flow direction of the Mahakam river as far upstream as Samarinda, located about 20 km upstream from the delta apex (Fig. 1(b)). The wave energy that affects the delta is very low. Low wind speed and the short fetch in the Makassar Strait result in a significant wave height of less than 0.6 m (Roberts and Sydow 2003). Furthermore, the shallow submerged delta-front platform, which extends to the 5 m isobath several kilometers offshore (Fig. 1(b)), dissipates wave energy so that only low-energy waves reach the coastline.

The present Mahakam river drains about 75,000 km^2 of the Kutei Basin shown in Fig. 1(a) was a part of the uplifting central Kalimantan ranges. From available rainfall data and the size of the drainage basin, a mean water discharge was evaluated as the order of value ranging from 1800 to 2800 m^3 s^{-1} with large seasonal variations (Allen and Chambers 1998). Floods up to 5000 m^3 s^{-1} may occur in the upper and middle reaches of the catchment, which is separated from the river mouth of the drainage basin by a subsiding area characterized by a low relief alluvial plain and several large lakes, located about 150 km upstream of the delta plain (Roberts and Sydow 2003). The lakes create a buffer causing the damping of the flood surges (Storms et al. 2005) and effectively level the Mahakam river floods, resulting in a constant discharge for lower reaches of the Mahakam river and delta system. The absence of peaks in river discharge has resulted in a delta plain that has no natural levees or crevasse splays. The climatic conditions are tropical, with only a slight monsoon impact. Rainfall ranges from about 4000 to 5000 mm per year in the central highlands to 2000 to 3000 mm per year near the coast (Roberts and Sydow 2003) and has a high in January and a low in August.

The objective of this study is to elucidate the spatial and

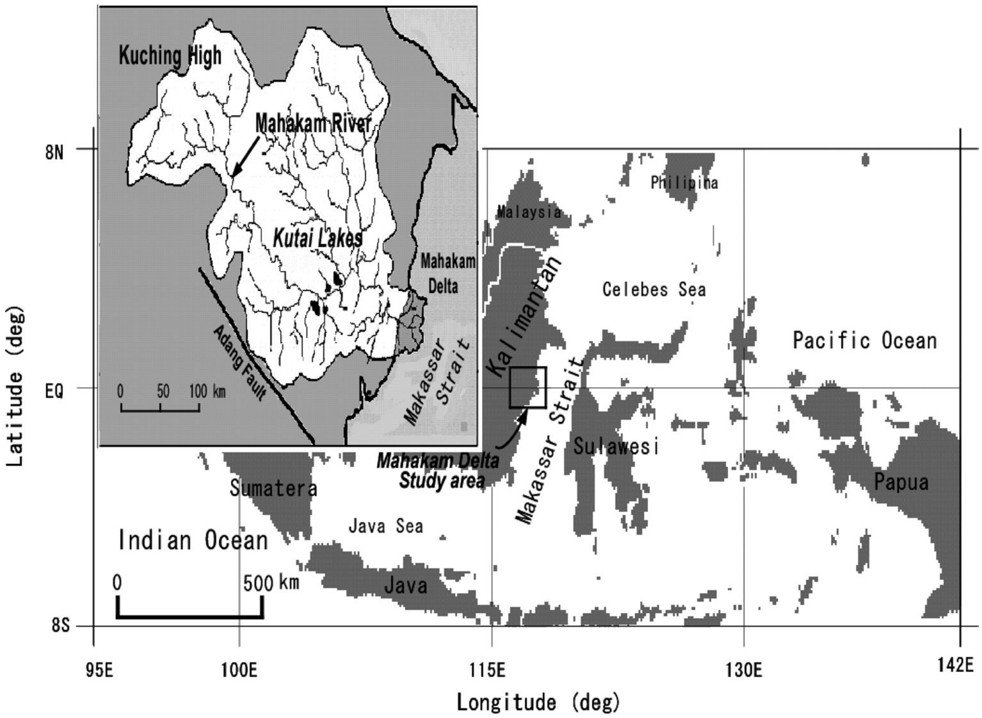

Fig. 1(a). Location map of the Mahakam delta (study area) on the east of Kalimantan, Indonesia and Mahakam River Drainage Basin (Allen and Chambers, 1998).

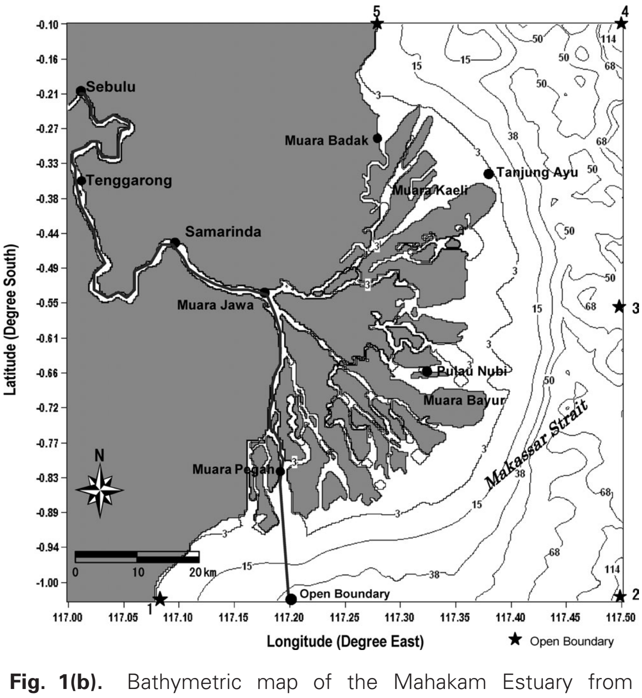

Fig. 1(b). Bathymetric map of the Mahakam Estuary from DISHIDROS of Indonesian Navy. Numbers show the depth in meters.

temporal variations in tidal levels and tidal currents using numerical model, which will be compared with the observed data. Tidal currents are thought to play a very important role for the transport of suspended sediments in the Mahakam river and to be responsible for the delta morphology formation, but there has been no study on the tidal levels and tidal currents in the Mahakam river. The used hydrodynamical model is a state of the art two dimensional time dependent model. This module of ECOMSED (Estuarine Coastal and Ocean Modeling System with Sediment), developed by HydroQual, Inc. (2002), has been successfully applied to the coastal and estuarine waters. Some recent applications of the module include Chesapeake Bay (Blumberg and Goodrich 1990), Delaware Bay and Delaware River (Galperin and Mellor 1990), the Gulf Stream Region (Ezer and Mellor 1992). The development of ECOMSED was originated in the mid 1980's with the creation of the Princeton Ocean Model (Blumberg and Mellor 1987).

Materials and Methods

Observation

Bathymetry data of the model domain were obtained from DISHIDROS (Indonesian Navy Hydrographic Department) of Indonesian Navy (Fig. 1(b)). The model domain in this study covers the area of Mahakam delta (0°10′00″S–1°03′00″S and 116°59′00″E–117°49′14″E), offshore area of approximately 30 km from Muara Bayur toward the Makassar Strait and toward upstream from Muara Pegah up to Sebulu which passes through the Samarinda city (Fig. 1(b)).

Time series of water surface elevation and current data were obtained from the IMAU (Institute for Marine and Atmospheric Research Utrecht University, the Netherland) which conducted the field observation in the Mahakam delta

Table 1.

Constituent	Amplitude and Phase	Sta. 1	Sta. 2	Sta. 3	Sta. 4	Sta. 5
S_2	Amplitude (m)	0.465	0.468	0.468	0.478	0.478
	Phase (deg)	322.57	322.54	322.54	322.57	322.50
M_2	Amplitude (m)	0.699	0.699	0.699	0.646	0.647
	Phase (deg)	276.88	276.04	276.04	278.38	278.37
K_1	Amplitude (m)	0.221	0.224	0.224	0.211	0.211
	Phase (deg)	159.02	160.27	160.27	156.66	156.40
O1	Amplitude (m)	0.164	0.165	0.165	0.159	0.159
	Phase (deg)	139.36	140.45	140.45	137.22	137.03

during the period of 30 June–8 July 2003 (the south east monsoon). Water surface elevation and current velocity were measured using a pressure sensor and ADCP (the Acoustic Doppler Current Profiler), respectively. The data were sampled at Muara Jawa (Fig. 1(b)) at the depth of 4.0 m from the surface and utilized to verify and validate the model results.

Numerical simulation

Governing equations

The tide-induced motion in the coastal sea is generally described by the conservation law of momentum and water mass. They are the equations of motion along E-W ($\overline{U}$) and N-S ($\overline{V}$) directions,

$$\frac{\partial \overline{U}}{\partial t}+\frac{\partial \overline{U^2}}{\partial x}+\frac{\partial \overline{UV}}{\partial y}-f\overline{V}=-g\frac{\partial \eta}{\partial x}+\frac{\tau_{bx}}{\rho_0 D}+A_H\Delta\overline{U}, \tag{3.1}$$

$$\frac{\partial \overline{V}}{\partial t}+\frac{\partial \overline{UV}}{\partial x}+\frac{\partial \overline{V^2}}{\partial y}-f\overline{U}=-g\frac{\partial \eta}{\partial y}+\frac{\tau_{by}}{\rho_0 D}+A_H\Delta\overline{V}, \tag{3.2}$$

and the continuity equation:

$$\frac{\partial D\overline{U}}{\partial x}+\frac{\partial D\overline{V}}{\partial y}+\frac{\partial \eta}{\partial t}=0, \tag{3.3}$$

where $\overline{U}$ and $\overline{V}$: the vertically integrated velocities in x and y direction [m s^{-1}]

D : the total depth ($=H+\eta$)

H : the depth

η : the surface elevation

τ_{bx} and τ_{by}: bottom stress in x and y direction ($=\rho_0\gamma_b^2(\overline{U}\sqrt{\overline{U^2}+\overline{V^2}}$) and $=\rho_0\gamma_b^2(\overline{V}\sqrt{\overline{U^2}+\overline{V^2}}$))

ρ_0: the density of water ($=1024.78$ kg m^{-3})

ρ_b^2: the bottom frictional coefficient ($=0.0025$)

A_H : the coefficient of horizontal eddy viscosity [m^2 s^{-1}]

g : the gravitational acceleration [9.8 m s^{-2}]

f : the Coriolis parameter ($=2\Omega \sin \phi$; $\Omega=7.27\times10^{-5}$ s^{-1} and ϕ is the latitude)

Δ : the Laplace Operator for 2 Dimensional ($=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$).

The horizontal eddy viscosity is given on the basis of Smagorinsky formula,

$$A_H=C\Delta x\Delta y[(\partial\overline{U}/\partial x)^2+(\partial\overline{V}/\partial y+\partial\overline{U}/\partial y)^2+(\partial\overline{V}/\partial y)^2]^{1/2}, \tag{3.4}$$

where C is a constant ($=0.20$) and Δx and Δy are horizontal mesh sizes ($\Delta x=\Delta y=200$ m).

Boundary conditions

Along the open boundary, the tidal elevation is prescribed by the linear interpolation using harmonic constant of M_2, S_2, K_1 and O1 constituents at five points (1, 2, 3, 4, 5) with star marks (see Fig. 1(b)) given by ORI.96 model, which are shown in Table 1. ORI.96 ocean tide model was developed at Ocean Research Institute, University of Tokyo. The ORI.96 model provides grid values of harmonic constants of pure ocean tide (0.5×0.5 degrees) and radial loading tide (1×1 degrees) for 8 major constituents (Matsumoto et al. 1995).

The averaged monthly river discharge data of the Mahakam river (1993–1998) obtained from the Research and Development Irrigation Ministry Public Work, Republic of Indonesia are shown in Fig. 2. The average river discharge in June and July 2040 m^3 s^{-1} was given at Sebulu in Fig. 1(b).

Numerical experiment

The governing equations (3.1), (3.2) and (3.3) require the numerical computational methods discretized by staggered computation "C" grid with grid sizes of $\Delta x=\Delta y=200$ m, resulting in 468×490 grids covering the study area. Time step for the calculation is 3.0 s. The integration was carried out for 360 hrs (15 days) in all. In the experiment, the surface wind stress is neglected. The water density is considered to be constant of 1024.78 kg m^{-3}.

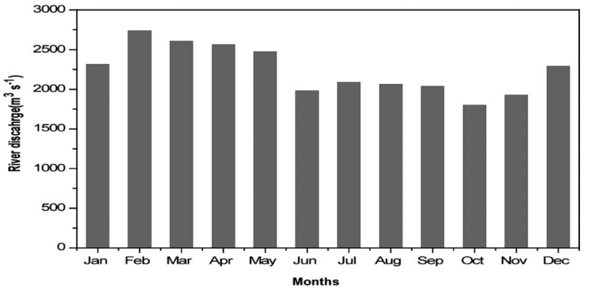

Fig. 2. The monthly river discharge ($m^3 s^{-1}$) data of the Mahakam river (1993–1998).

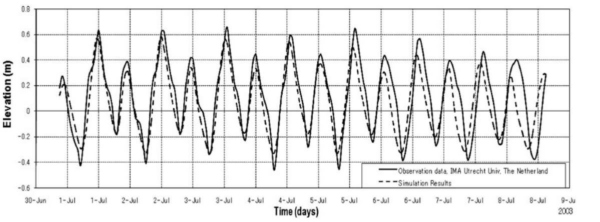

Fig. 3. Verification of elevation between the observation data (IMAU Utrecht Univ.) and the simulation results at Muara Jawa for the period of 30 June to 08 July 2003.

Results

Verification of elevation and current velocity

Figure 3 shows the comparison of the observed elevation data at Muara Jawa (Fig. 1(b)) with the model results for the corresponding 15 days period (27 June–12 July 2003). The RMS (root mean squared) error for both datasets was 0.15 m.

The current verification of simulation result was conducted at Muara Jawa (Fig. 1(b)). Verification graph was shown in Fig. 4. The current velocity component of x direction (U; eastward) indicates that simulation results are a little bigger than the observation data. Figure 4 shows that x component has an appropriate phase with observation data in almost every condition with RMS error of $0.05\ m\ s^{-1}$.

Tide and tidal current

Figures 5 and 6 show the power spectra of observed and simulated elevations and current velocities, respectively. The tidal amplitude and current velocity spectra in the Mahakam river (Muara Jawa) show the same peaks between observation data and simulation results. There are three peaks in Figs. 5 and 6 around 12.8 hrs (M_2) and 12.2 hrs (S_2), around 23.3 hrs (K_1) and 25.6 hrs (O_1), and at 6.2 hrs (M_4). The disagreement between observation and simulation from 15 hrs to 20 hrs period may be due to the coarse resolution of the model. The temporal variation of elevation along the Mahakam Estuary and open boundary (Fig. 1(b)) from 2 to 3 July 2003 (spring tide) are shown in Fig 7. Wave form is changed from the mouth of the estuary to upstream and the semi-diurnal tide is distorted to upstream. Time from low water to high water becomes shorter to upstream.

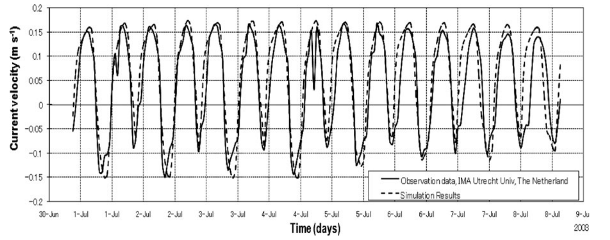

Fig. 4. Verification of the current velocity component U (x direction, east (+)–west (−)) between the observation data (IMAU Utrecht Univ.) and the simulation results at Muara Jawa at the depth of 4.0 m from the surface for the period of 30 June to 08 July 2003.

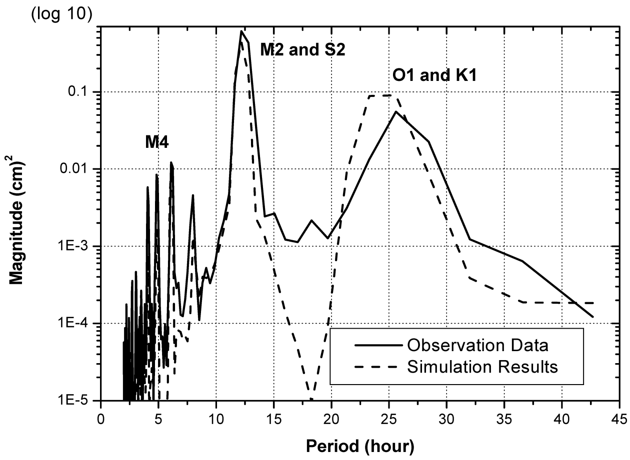

Fig. 5. Spectral analysis of the observed and simulated elevations.

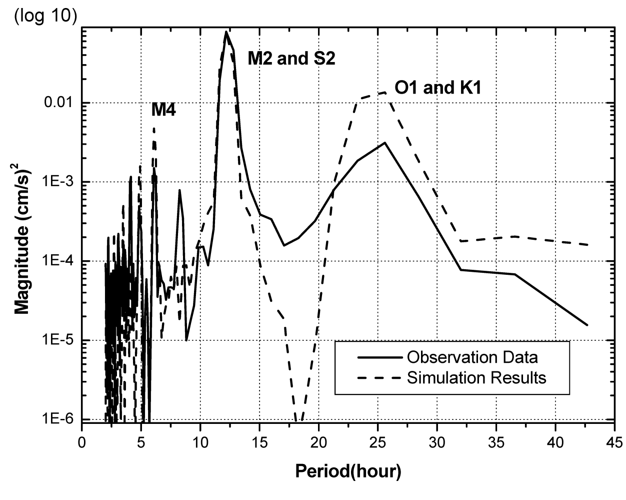

Fig. 6. Spectral analysis of the observed and simulated current velocity.

Figure 8 shows the spatial variation of M_4, M_2, S_2, K_1, and O_1 tidal amplitudes along the axis of the Mahakam Estuary from Sebulu to the open boundary (see Fig. 1(b)). In the offshore area (from the open boundary to Muara Pegah), the M_2 constituent has the largest amplitude, followed by S_2, K_1, and O_1. The M_2 amplitude is highest at open boundary,

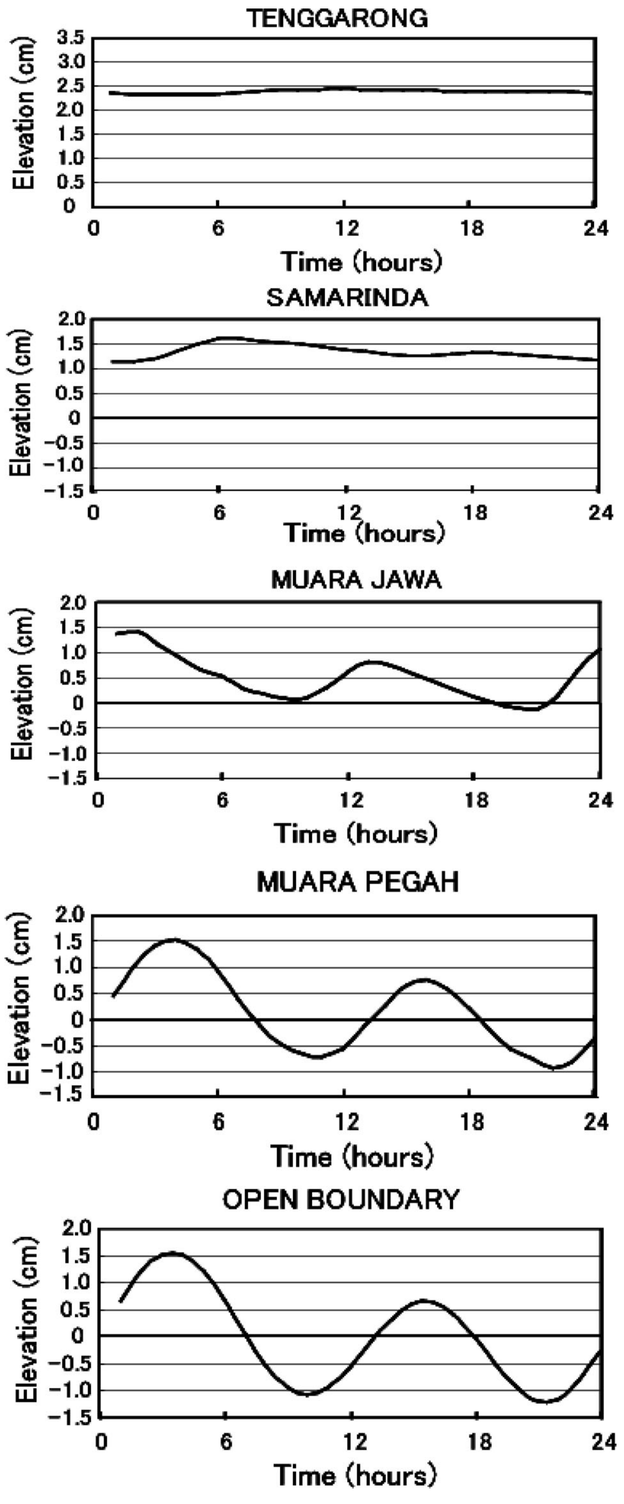

Fig. 7. Temporal variation of elevation along the Mahakam Estuary. Position of Tenggarong, Samarinda, Muara Jawa, Muara Pegah and Open boundary are shown in Fig. 1(b).

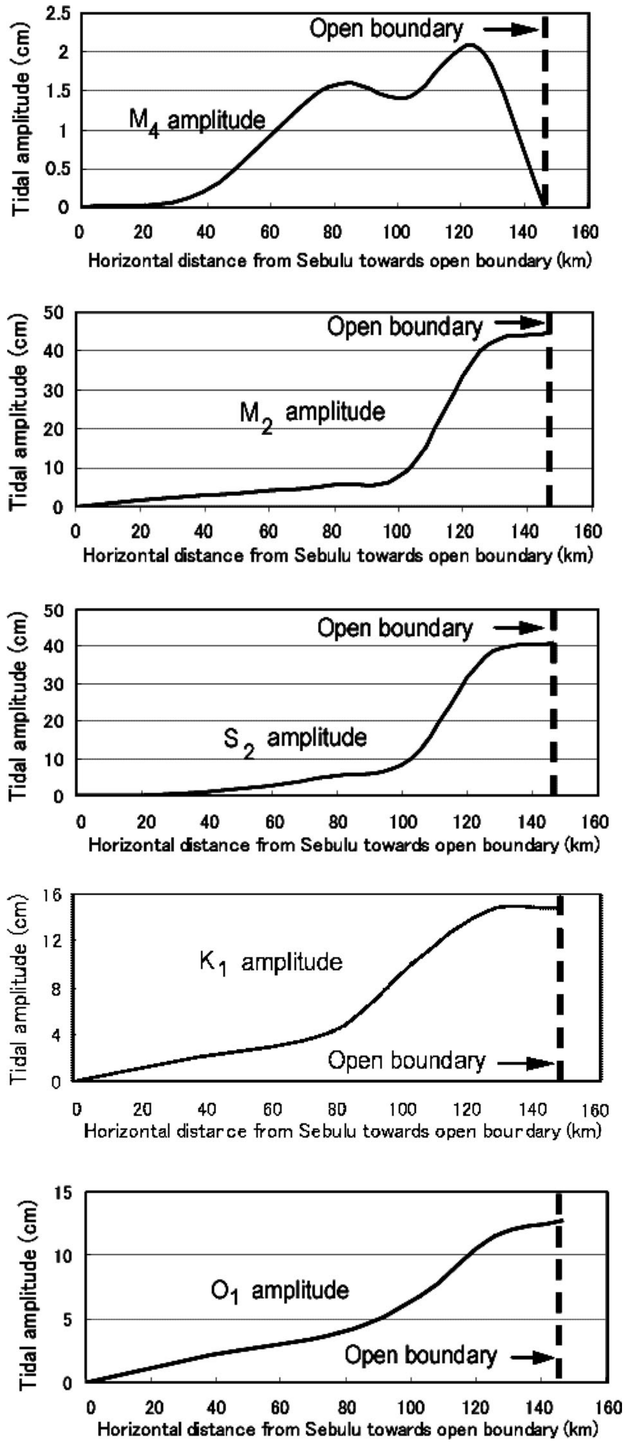

Fig. 8. Spatial variation of M_4, M_2, S_2, K_1, and O_1 tidal amplitudes along the axis of the Mahakam estuary.

reaching 44 cm.

The semi-diurnal tidal amplitude peaks at the open boundary and then begins to decrease steadily upstream of Muara Pegah along the main stream of the Mahakam river.

The diurnal K_1 tidal amplitude peaks between the open boundary and Muara Pegah. The natural oscillation period of the Mahakam Delta $T_n 4L/\sqrt{gh} = 19$ hrs, where L (140 km) is the length from Sebulu to Muara Pegah, g (9.8 $\mathrm{ms^{-2}}$) is gravitational acceleration, and h (7 m) is the average water depth of the estuary. The natural oscillation period T_n is near diurnal tidal period and far from semi-diurnal tidal period. Therefore the decrease of diurnal tidal amplitude is smaller than that of semi-diurnal tidal amplitude.

The amplitude of tidal wave propagating towards upstream from Muara Pegah becomes almost zero near Sebulu due to the friction.

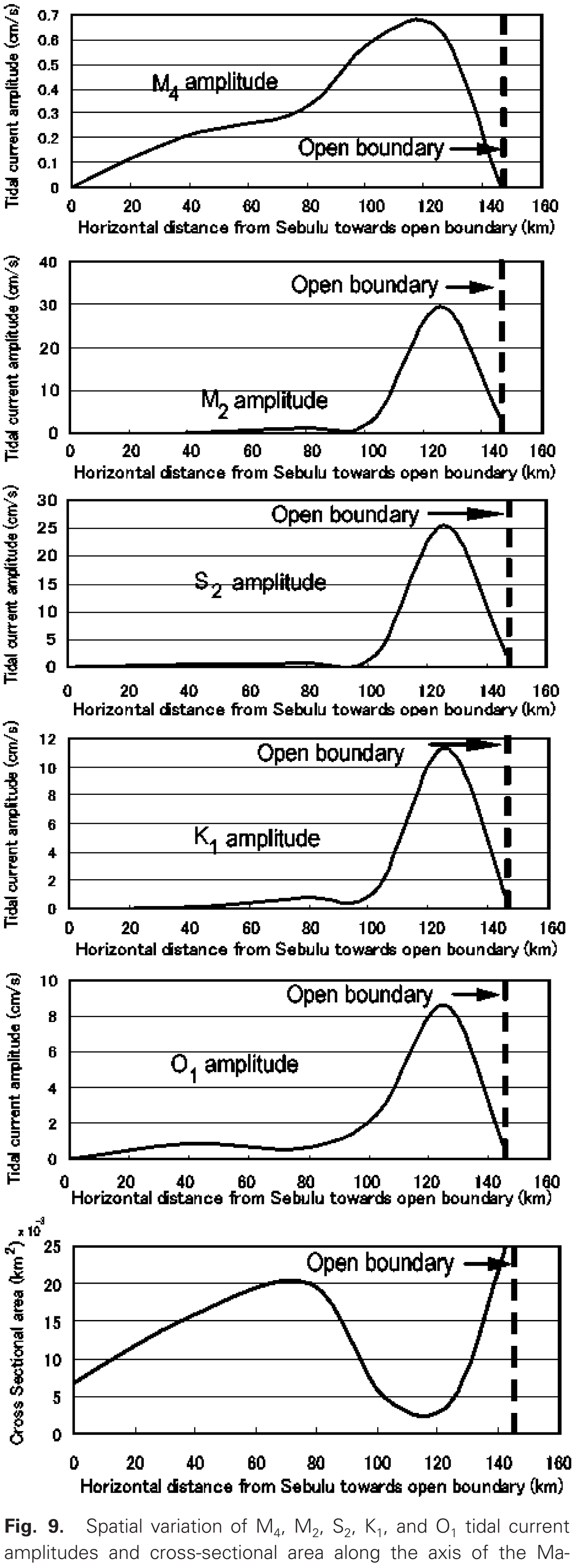

Fig. 9. Spatial variation of M_4, M_2, S_2, K_1, and O_1 tidal current amplitudes and cross-sectional area along the axis of the Mahakam estuary.

The spatial variations in calculated tidal current amplitudes are shown in Fig. 9. The semi-diurnal and diurnal tidal currents amplitude increases significantly from the open boundary towards Muara Pegah. Furthermore it decreases significantly from Muara Pegah towards upstream. The tidal current amplitude is strongly influenced by the cross sectional area and the friction.

The M_4 tidal current amplitude distribution follows the M_2 tidal current amplitude distribution with its peak at mid estuary (about 120 km from Sebulu), whereas M_4 tidal elevation amplitude has another peak farther upstream (about 80 km from Sebulu) as shown in Fig. 8. This is due to the shrinking of the cross-sectional area from 60 km to 80 km from Sebulu as shown in Fig. 9.

In the Mahakam estuary, tidal elevation amplitude distortion (M_4/M_2) is less than 0.3 as shown in Fig. 10. For tidal

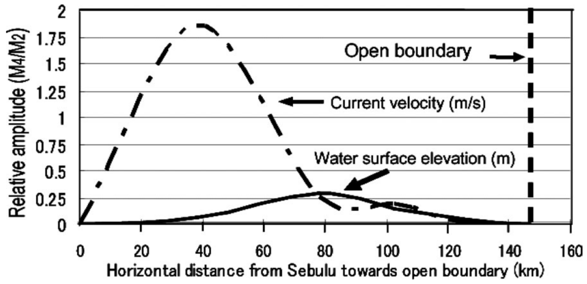

Fig. 10. Spatial variations of M_4/M_2 tide and tidal current amplitudes along the axis of the Mahakam estuary.

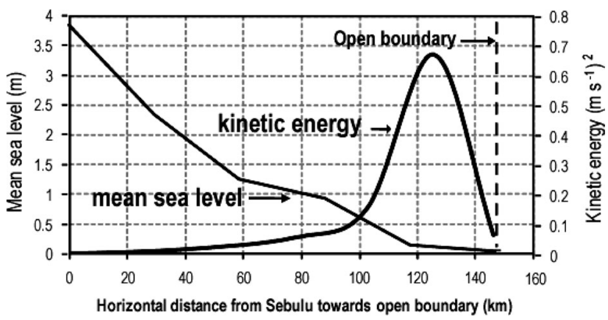

Fig. 11(a). Spatial variation of mean sea level and the averaged tidal current kinetic energy along the axis of the Mahakam estuary.

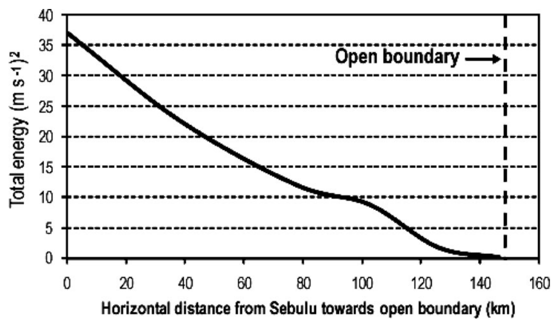

Fig. 11(b). Spatial variation of the total energy along the axis of the Mahakam estuary.

current amplitude, M_4/M_2 reaches a maximum of 1.85 at Tenggarong (about 40 km from Sebulu) due to the decrease of the cross-sectional area from Samarinda to Tenggarong.

The distortion of M_2 tidal wave in shallow estuaries plays an important role in sediment and salt transport (Blanton et al., 2002). Factors such as friction and channel morphology generate shallow water overtides such as M_4 constituent.

Figures 11a and 11b show the spatial variations in the mean sea level, the averaged tidal current kinetic energy, and total energy along the axis of the Mahakam Estuary. The averaged tidal current kinetic energy is nearly zero at open boundary, becomes 0.67 $(\mathrm{m\,s^{-1}})^2$ at Muara Pegah but decreased towards upstream and it is almost zero at Sebulu. The total energy increases from the open boundary to upstream, reaching 37 $(\mathrm{m\,s^{-1}})^2$ because the potential energy increase to upstream.

The simulated tidal current patterns in the Mahakam Estuary are shown in Fig. 12(a) to (d). Tidal elevation at Muara Bayur in Fig. 1(b) is chosen as the reference time of the flood and ebb conditions. The existence of currents with back and forth motion representing flood and ebb conditions.

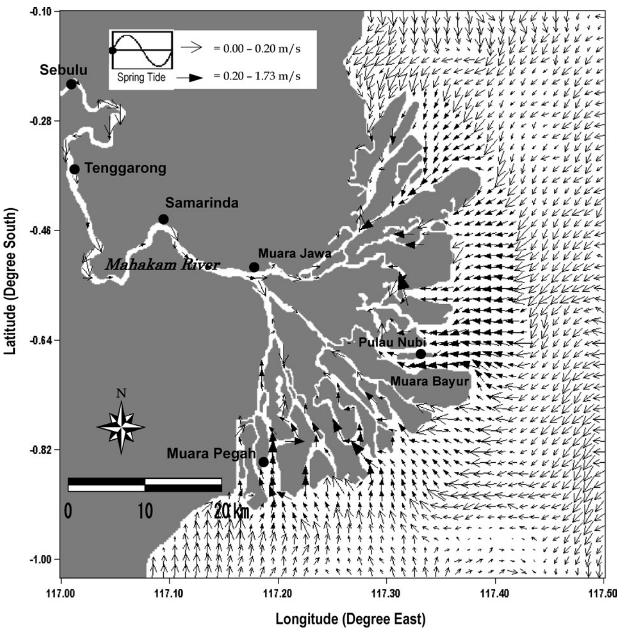

Fig. 12(a). Tidal current during a maximum flood in spring tide condition.

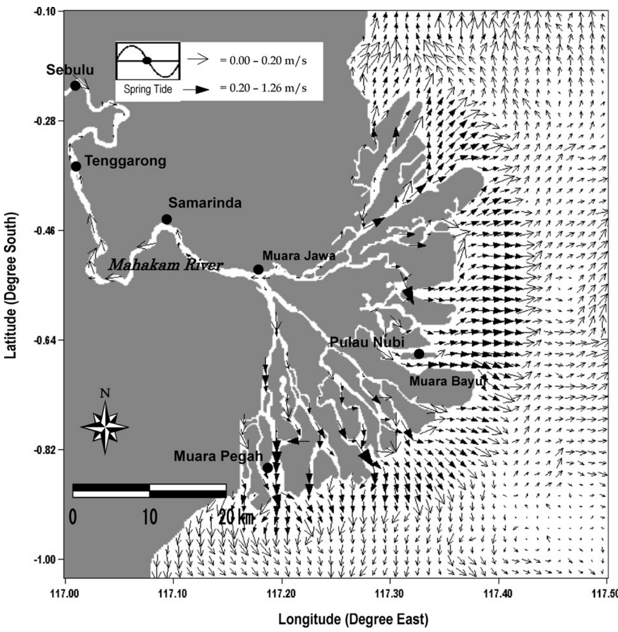

Fig. 12 (c). Tidal current during a maximum ebb in spring tide condition.

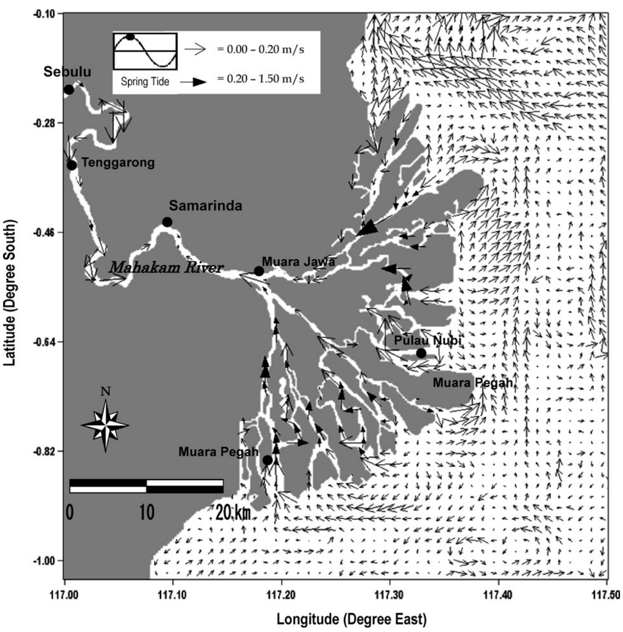

Fig. 12(b). Tidal current for high water in spring tide condition.

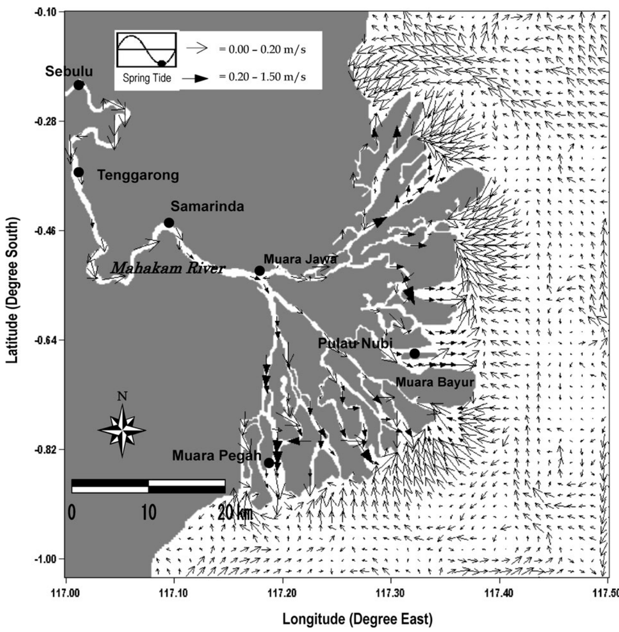

Fig. 12(d). Tidal current for low water in spring tide condition.

Figure 12(a) shows the current during a maximum flood in spring tidal condition. The current flows from the Makassar Strait to the delta waters. The current velocity at offshore area is about 0–0.2 m s^{-1}, when the tidal wave enters into the narrow delta area the current velocity becomes bigger and reaching ± 1 m s^{-1}. In the Mahakam river area from Sebulu to Muara Pegah the current flows to the offshore area.

Figure 12(b) shows the current for high water in spring tidal condition. Generally, the current velocity at offshore area is weaker than that at flood condition because the current starts to flow in the opposite direction. The currents flow from the offshore area into the Mahakam river area from Muara Jawa to Samarinda, while in Mahakam river area currents flow from Sebulu towards Samarinda. During the ebb tidal condition the current from the Mahakam Delta area flows towards the offshore area (the Makassar Strait), while at the Mahakam river area currents flow from Muara Jawa towards upstream as shown in Fig. 12(c).

Figure 12(d) shows the current pattern at low water in spring tidal condition. The figure shows the contrary with that at high water condition (Fig. 12(b)). The currents flow from the offshore area towards the delta area with the speed of about 0.20 m s^{-1}, while at the Mahakam river area the flow pattern is from upstream towards delta area with the speed of about 1.5 m s^{-1}.

Discussion

In this numerical simulation the results clearly indicate that the tide is the main driving force affecting the water level in the Mahakam estuary. The currents in the Mahakam delta waters are mostly affected by tides and river flow. During the flood tide the current flows to the delta waters, and vice versa in the ebb tide. Such tidal current occurs according to the tidal wave behavior in the Mahakam delta.

The RMS (root mean squared) error in the model elevation and current velocity are 0.15 m and 0.05 m s^{-1}, respectively, with the average tidal amplitude of 0.6 m and tidal current amplitude of 0.15 m s^{-1}. The wave form is changed from the mouth of the estuary to the upstream. The semi-diurnal (M_2, S_2) tidal amplitude peaks at the open boundary and then it begins to decrease steadily upstream along the main stream of the Mahakam river. The diurnal (K_1, O_1) tidal amplitude peaks between the open boundary and Muara Pegah. The decrease of diurnal tidal amplitude is smaller than that of the semi-diurnal tidal amplitude. This is due to the natural oscillation period of the Mahakam Estuary (19 hrs) is near the diurnal tidal period but is far from the semi-diurnal tidal period. In the Mahakam estuary, tidal amplitude distortion (M_4/M_2) is less than 0.3.

Future work would consist of expanding to three-dimensional baroclinic hydrodynamical model in order to simulate temperature and salinity distribution, and the sediment transport.

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