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Tidal impact on river discharge in the Mahakam River and Distributary Channels, East Kalimantan, Indonesia

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SUMMARY

Many of the world's lowland rivers are influenced by tidal motion. River-tide interaction originates from frictional effects due to variable tidal amplitudes generating nonsteady gradients in the subtidal water level. In lowland rivers, the region of influence of low-frequent surface level variations potentially reaches further inland than the point of tidal extinction. Here we present first results of an investigation into the mechanisms of river-tide interaction in the Mahakam river and tidal channels, based on fieldwork data and numerical modelling. Wavelet analysis of the resulting water levels indicates that tidal oscillation in the semidiurnal and diurnal band bypasses the lakes region while subtidal oscillation (mainly concentrated in the fortnightly band) influences the region of the lakes and further upstream. Consequences for river discharge are discussed.

1. INTRODUCTION

The Mahakam is a tropical river located on the eastern shore of Kalimantan (Borneo), Indonesia. The river mouth is separated from the upper reaches of the catchment by a low relief alluvial plain located about 150 km upstream (Figure 1). A system of interconnected lakes with a total area of about 400 km^2 acts as a buffer that damps flood surges, resulting in a relatively constant discharge in the lower reaches of the river. At the apex, the Mahakam drains into a regular fan-shaped delta composed of a quasi-symmetric network of rectilinear distributaries and sinuous tidal channels. The Mahakam delta is a low wave-energy, tide and fluvial dominated system that has been prograding 60 km over the past 5000 years [1]. It has been suggested that tidal processes have a dampening effect on the fluvial dynamics of the delta region, leading to the characteristic progradation pattern [1]. Recently, this was ascribed to the non-flooding discharge regime of the lower Mahakam catchment area, under the influence of the buffering effect of the lakes system [14]. As the river settles over a relatively flat subsiding basin, explaining a mild surface level slope, water level fluctuation induced by the tide can be measurable up to the lakes region, and even further upstream during dry periods. Tidal processes, therefore, may have an influence on the downstream discharge regimes due to the forcing of water levels in the lakes.

The interaction between river and tidal flows can be understood from an analysis of the bottom friction term in the momentum balance equation. In shallow rivers, frictional forces highly exceed forces associated with inertial accelerations. Therefore, fortnightly fluctuations in water level arise as a consequence of fortnightly variation in friction [10,3]. In rivers and distributary channels accommodating both tidal and river discharges, a low-frequency compound tide of fortnightly periodicity (~14.8 days) is generated by non-linear interaction of the M_2 and S_2 constituents when a net current flowing downstream is present [5]. The Mahakam river and distributary channels are subject to a mixed, mainly semidiurnal tidal regime. Therefore, the non-linear interaction of K_1 and O_1 constituents also generate a low-frequency compound tide of fortnightly periodicity (~13.5 days). We aim to understand the tidal impact on discharge dynamics in the Mahakam river and distributary channels. Here we present first results of an investigation into the mechanisms of river-tide interaction along the Mahakam river and delta, based on fieldwork data and numerical modelling.

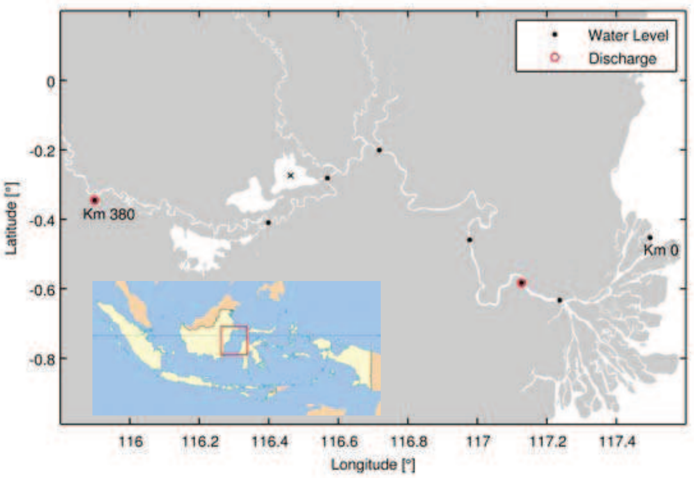

Figure 1: Map of the Mahakam river in Borneo, Indonesia, with locations of the measuring stations along the river. The station inside the lakes, indicated with a cross, represents only numerical model output.

2. METHODS

A measuring network was set up along the lower 400 km of the river (Figure 1) for about 18 months. It consisted of several water level gauges, distributed along the river and in the delta, and two horizontally deployed acoustic Doppler current profilers (H-ADCPs) located upstream and downstream of the lakes region. The measuring protocol of the pressure sensors was set to collect one minute averages every 15 minutes, while that of the H-ADCPs was set to collect 10 minute averages every 30 minutes. Both instruments were recording at 1 Hz. Velocities measured with the H-ADCP were converted to river discharge using conventional ADCP shipborne discharge measurements. At the downstream discharge station, where tides dominate, seven 13h ADCP campaigns were carried out spanning over high- and low-flow conditions during spring and neap tides. Upstream the lakes, eight 6h ADCP campaigns also covered a wide range of flow conditions. Details of the procedures to convert flow velocity across the river section into water discharge can be found in [7] and [12]. An intensive bathymetric survey with a single-beam echo-sounder was conducted along the river, its tributaries, the three lakes and the delta region. Transect data across the river were interpolated onto a curvilinear grid [11] to produce the bathymetric map of the river.

A depth-integrated version of the unstructured mesh, finite-element model SLIM (Second-generation Louvain-la-Neuve Ice-ocean Model) was used. Finite-element was preferred over the traditional finite-difference approach as the tidal motion in the delta is characterised by a wide range of temporal and spatial scales. Unstructured grids allowed us to refine the mesh in the narrow channels of the delta, keeping a good representation of the hydrodynamics and avoiding excessive computational power [2]. Two 2D computational domains were defined to cover the Mahakam delta and the lakes, which were connected to a 1D computational domain representing the river and its tributaries. Measured bathymetry was interpolated to the modelling grid in all domains except for the outer delta and continental shelf parts, where GEBCO database data were used. The model was forced with tides from the global ocean tidal model TPX07.1 at open boundaries, located far away from the delta and stretching across the entire Makassar Strait. The upstream boundary of the main tributary in the model coincides with the upstream discharge measurement station. At five secondary tributaries, discharge was generated using rainfall-runoff modelling results [6]. The slope of the river was set to 1×10^{-5}, bottom friction was decreased from n = 0.023 in the outer delta to n = 0.017 at the river mouth and set to n = 0.017 along the remainder of the river. This variation is a first rough estimate accounting for the gradual transition between marine and riverine environments. Numerical simulations were carried out in order to calibrate the model [13].

3. RESULTS

Time series of flow velocity from model and observations at the downstream discharge station were subjected to a Continuous Wavelet Transform using a Morlet mother wavelet. Wavelet analysis was preferred over traditional harmonic analysis because of its ability to deal with non-stationary signals [8]. Wavelet amplitudes corresponding to quarterdiurnal (U_4), semidiurnal (U_2) and diurnal (U_1) fluctuations were obtained from the spectrograms and averaged over a one day period to obtain the subtidal amplitude variation. Velocity series were also averaged to obtain U_0, the subtidal velocity. Time series of U_0, U_1, U_2 and U_4 from the discharge station downstream of the lakes are shown in Figure 2. The subtidal component U_0 ranges between 0.2 and 0.8 m/s. The semidiurnal species dominate the tidal velocity fluctuations, featuring more variation in amplitude minima than in amplitude maxima. Spring-neap variation of U_2 is primarily modulated by seasonal variation, while that of U_1 peak every ~29 days, coinciding with the equatorial passage of the moon [9]. Values of U_4 covary with U_2. Some variation in U_2 amplitude can also be attributed to the discharge peak during May-July, which is supported by an increased damping in water levels along the river (not shown). Overestimation of the amplitudes of measured and modelled velocity may arise mainly due to underestimation of the friction coefficient used in the simulations. Figure 2 also shows the wavelet coherence of the two time series for the subtidal band. A high agreement is seen at the 14 days period band and at periods between one to two months, coinciding with the observed fortnightly and river discharge fluctuation (respectively).

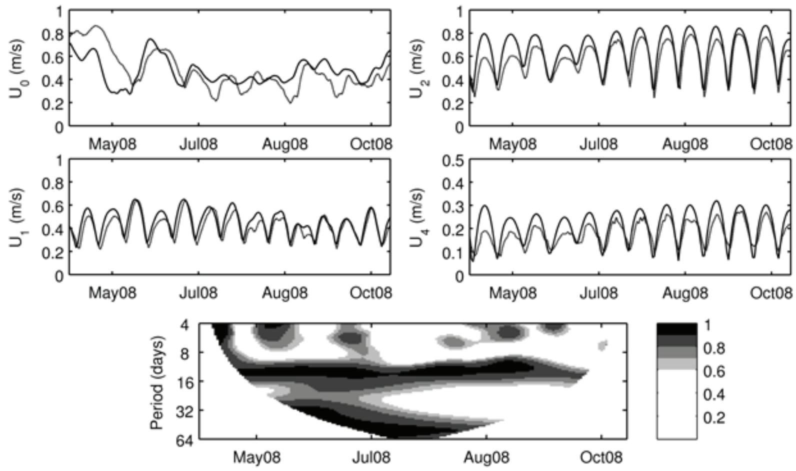

Figure 2: Subtidal velocity (U_0) and velocity amplitude of the three main tidal species (U_1, U_2 and U_4) for model (full line) and observation (dashed line) at the discharge station downstream the lakes. Lower panel: wavelet coherence between model and observation for the subtidal band.

Figure 3 shows time-frequency representations of water levels obtained with the numerical model at the stations depicted in Figure 1. When progressing upstream, the diurnal and semidiurnal tidal components damp and manage to bypass the lakes region, although they cannot reach inside the lakes because they are fully damped as a result of the large surface area of the lake (station indicated with an x in Figure 1). The fortnightly component amplifies upriver, even reaching the lakes region and further upstream. During a discharge peak (May-July), fortnightly oscillations are damped downstream the lakes, possibly as a consequence of enhanced tidal damping due to increased river discharge. Close to the lakes and upstream, fortnightly oscillations exist although the corresponding band merges with that representing lower frequency oscillations, induced by river discharge.

4. DISCUSSION

Although the numerical model has to be further calibrated and validated with observations both in the distributary channels and along the river, the results indicate that fortnightly oscillations in water level have a significant impact on discharge regimes of the lower Mahakam channels. Due to the large storage area, river-tide interaction generates significant low-frequent oscillations in the river discharge. As the fortnightly water levels amplify towards the lakes region, backwater effects, which are felt further upstream, enhance the fortnightly component of river discharge because of the water storage in the lakes. Figure 3 shows amplitudes of fortnightly water level oscillations to become more variable when going upstream. The amplitudes of fortnightly oscillations decreases when tides are damped by an increased river discharge. As river discharge hardly shows any variation in the period between August and November, tidal damping in that period can be attributed partly to the fortnightly component of river discharge. The influence of the forced fortnightly tide then creates a complex feedback mechanism between tides and river discharge. Observations suggest a strong fortnightly component in river discharge, measured downstream of the lakes. Numerical simulations support the observations. Subtidal fluctuations in water level as a result of river-tide interaction affect the entire river up to the lakes and upstream. Further investigation should reveal the gradual adaptation of water level to the subtidal dynamics induced by river-tide interaction.

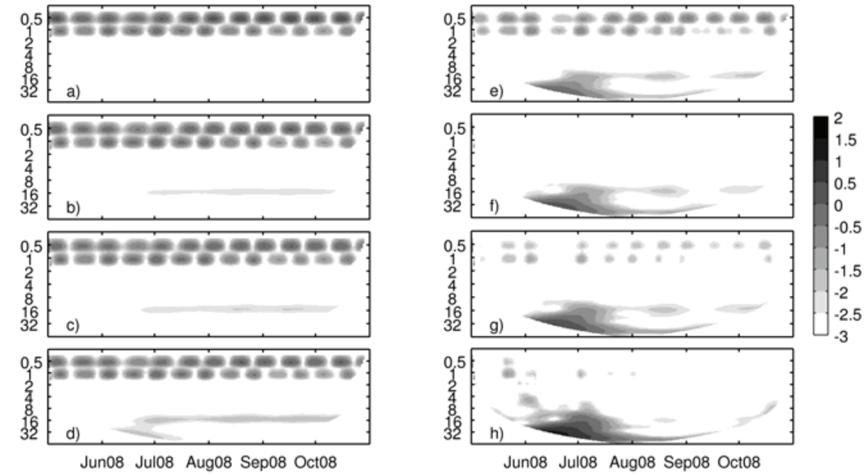

Figure 3: Time-frequency representation of water level at the stations along the Mahakam river: a) outer delta, b) river mouth, ~40 km, c) downstream discharge station, ~60 km, d) ~100 km, e) ~190 km, f) inside the lakes, ~220 km, g) 260 km, h) upstream discharge station, ~380 km. Vertical axes represent period in days. Contours depict logarithm base two of wavelet amplitude.

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