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Analysis and numerical modeling of the flow and sand dynamics in the lower Song Hau channel, Mekong Delta

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ABSTRACT

Two- and three-dimensional Delft3D Flow and Morphology models were constructed for the lower Song Hau distributary channel of the Mekong River in Vietnam to provide insights into the hydrodynamics and sand transport of the channel system. The models were calibrated and validated with data for observed water level, water discharge, velocity, and suspended-sand concentration during the high- and low-flow seasons of 2014 and 2015. The water and sand budgets of the Dinh An and Tran De channels, the two sub-distributaries of the lower Song Hau channel, were calculated, showing that ~73% of the fluvial water discharge and ~90% of suspended sand were transported through the Dinh An channel, while the rest was transported through the Tran De channel in the high-flow season. In the low-flow season, the total fluvial water discharge was < 20% of that in the high-flow season; and ~96% of it was transported through the Dinh An channel and the rest was transported through the Tran De channel. Sand was transported from channels into the ocean in both the Dinh An and Tran De channels during the high-flow season, but from the ocean into the two channels during the low-flow season. The reversed sand flux from ocean into river channels during low-flow season was not observed in field studies. The different behaviors between models and field observations might be caused by the absence of baroclinic effects in the model set up. The Dinh An channel was found to be dominated by ebb tide, in favor of transporting water and sediment to the ocean, and the Tran De channel was dominated by flood tide. In the high-flow season, the residual currents were directed toward the ocean for both the Dinh An and Tran De channels. In the low-flow season, the magnitude of the residual currents decreased in the river channels. Under these conditions, the residual-current direction changed to be ambiguous in the Tran De channel, but remained seaward in the Dinh An channel. The low fluvial discharge combined with strong tides under very low-flow conditions can probably generate a net clockwise water circulation between the Dinh An and Tran De channels, which transports water from the ocean to the river through the Tran De channel, then back into the ocean through the Dinh An channel. The clockwise circulation pattern is likely to influence the channel evolution and impact saltwater intrusion issue in the lower Song Hau channel.

1. Introduction

Over 350 million people live on river deltas, and the number is predicted to continue increasing (Timmermanab and White, 1997; Ericson et al., 2006; Overeem and Syvitski, 2009; Higgins, 2016). The evolution of river deltas is strongly influenced by the morphodynamics of lower reaches of river channels, which are governed by the interactions of fluvial runoff, tides, winds, waves, and the overall basin topography. The dynamics of lower-river channels determine fresh and saltwater plume expansion upon release to the continental shelf, as well as sediment transport between rivers and oceans (Wright and Coleman, 1974; Mossa, 1996; Wu et al., 2010; Nowacki et al., 2015). The understanding of lower-river channel flow and sediment dynamics is essential for the successful development of sustainable restoration and management strategies of rivers and deltas (Smith and Winkley, 1996; Frihy et al., 2003).

Major rivers and deltas around the world have been the focus of numerous hydrodynamic and sediment dynamic studies that demonstrate a wide variability in river-ocean exchange. For instance, the lower Mississippi River (annual average discharge: 530 billion m^3, average tidal range at the river mouth: 0.3 m, Allison and Neill, 2002; Rabouille et al., 2008) main channel is predominately governed by fluvial discharge and man-made engineering structures, the interactions of which have created a freshwater-dominated and non-reversing tidal

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channel that carries a large amount of sediment to the shelf during high- and average-flow conditions, but switches to a highly stratified estuarine system during low-flow period (Wright and Coleman, 1974; Allison et al., 2012). In the western distributaries of the Ganges-Brahmaputra Delta (annual average discharge: 993 billion m^3, average tidal range at the river mouth: 3.6 m, Jian et al., 2009; Walsh and Nittrouer, 2009), tides are the main control on sediment exchange with the ocean, which frequently modify the bed-layer sediment in the river channels. Sediment is imported into the river system through the flood-dominated channels and exported to the ocean through the ebb-dominated channels (Barua, 1990). During the dry season saltwater penetrates as far as 100 km inland from the Bay of Bengal (Allison, 1998). The lower Yangtze channels (annual average discharge: 925 billion m^3, average tidal range at the river mouth: 3.4 m, Hori et al., 2001; Hori et al., 2002; Rabouille et al., 2008) are also governed by tides, but highly influenced by the seasonal variations of fluvial discharge. An anti-clockwise circulation between the North Branch and the South Branch close to the river mouth has been discovered, which aggravates the saltwater intrusion issue and significantly influences the sediment-transport patterns (Xue et al., 2009; Li et al., 2010; Wu et al., 2010; Xu et al., 2012). These studies provide important information about the management of lower-river channels and delta systems. The lower Mekong River, which flows through the Mekong River Delta, and provides home for 18 million Vietnamese (Tuan et al., 2007), is controlled by tides and seasonal variations of fluvial discharge. The decreased freshwater flow in the lower Mekong channel modifies flow and sediment dynamics, and intensifies saltwater intrusion in the low-flow season (Gagliano and McIntire, 1968). Combining with the subsidence and sea-level rise, the Mekong Delta is predicted to experience significant changes in its future evolution (Ericson et al., 2006; Carew-Reid, 2008; McSweeney et al., 2010; Erban et al., 2014). The complexity of the system and the significant environmental changes require detailed study of the hydrodynamics and sediment transport in the lower Mekong channels, which is still inadequate (Wolanski et al., 1996, 1998; Nowacki et al., 2015).

Nguyen et al. (2008) estimated the fresh-water budget between the lower Mekong branches with a salt-water intrusion model, showing the general fresh-water distribution patterns in the multiple channels of the lower Mekong River system. More data and refinements are needed to improve the accuracy of this approach. Field observations have been undertaken in the Dinh An channel, the main distributary channel of the lower Song Hau channel of the Mekong River, showing the hydrodynamic and sediment-transport patterns in both the high- and low-flow seasons (Wolanski et al., 1996, 1998). There have also been extrapolation to estimate the annual sediment yield of the Mekong River (Nowacki et al., 2015). However, due to the difficulties and cost of field campaigns, both studies relied on observations collected for a short duration. The short duration does not allow accurate capture of the temporal variability for the sediment transport and increases uncertainties of the estimates. Koehnken (2012) argued that the importance of sand in the sediment dynamics of the Mekong River has been underestimated, and the substrates of the lower Song Hau channel system have been observed to be dominated by sand (Nowacki et al., 2015; Allison et al., 2017). Therefore, the sand dynamics likely play an important role in controlling the evolution of the lower Song Hau channel (Bravard et al., 2014). However, former studies have focused on the fine-sediment transport of the Song Hau channel (Wolanski et al., 1996, 1998; Hein et al., 2013; Nowacki et al., 2015; Thanh et al., 2017). Sand dynamics of the system, specifically in the Tran De distributary (another distributary of the Song Hau channel) and the interactions between the two distributaries, are still relatively unquantified.

In this study, numerical models (both depth-averaged (2D) and three-dimensional (3D)) were developed for the lower Song Hau distributary channel of the Mekong River, to study the detailed seasonal water and sand dynamics. The models were used to calculate water and sand budgets for the Dinh An and Tran De channels, and reveal the general patterns of water and sand movement of the lower Song Hau channel. The Lagrangian and Eulerian residual currents were also calculated to display the cumulative flow patterns. The flow dynamics under extreme low-flow condition were simulated to further explore the possible reversed flow patterns between the Dinh An and Tran De channels, which significantly influence the channel evolution and saltwater intrusion.

2. Regional setting

The Mekong River has a total length of 4,750 km and a drainage area of 832,000 km^2 (Xue et al., 2011). It has the 7th highest water discharge and 11th highest sediment discharge worldwide. The annual freshwater discharge of the Mekong River is 470 billion m^3 (Milliman and Syvitski, 1992). Current estimates of the annual sediment load for the Mekong River vary significantly from 40 to 160 Mt (Walling, 2008: 160 Mt/yr; Milliman and Farnsworth, 2011: 110 Mt/yr; Lu et al., 2014: 50–91 Mt/yr; Nowacki et al., 2015: 40 Mt/yr). Milliman and Farnsworth (2011) estimated that the annual dissolved sediment load is approximately 60 Mt.

The Mekong River bifurcates into the Song Hau and the Song Tien distributaries in the delta plain (Fig. 1A). The two distributaries ultimately divide into eight channels which flow into East Sea. This study focuses on the lower Song Hau distributary, which includes Dinh An and Tran De sub-distributary channels. The Song Hau distributary carries about 41% of the total Mekong water discharge, of which ~70% flows through the Dinh An channel and ~30% flows through the Tran De channel (Nguyen et al., 2008).

The Mekong Delta, through which the Song Hau flows, consists of flat terrain with an average elevation of 0.7–1.2 m. In the tidal and coastal areas, elevations range only between 0.3 and 0.7 m (VNMMP (Vietnam-Netherlands Mekong Delta Masterplan project project), 2011). Tropical monsoon conditions prevail in the Mekong catchment, including the delta area, and cause a clear seasonal boundary between dry and wet seasons. The dry season lasts from November to April and is dominated by the northeast winds and accounts for 20% of the annual rainfall. The wet season lasts from May to October and is dominated by southwest winds and brings 80% of the annual rainfall. In the delta area, the high-flow season usually begins in June and July and lasts until November or December. On the other hand, the low-flow season begins in January and lasts until May. Usually the maximum river discharge occurs in September and the minimum discharge occurs in April. Discharge in the high-flow season is about 25–30 times larger than that in the low-flow season (Öjendal, 2000). Saltwater intrusion is reported to expand far upstream when water levels drop below 70% of the average flow condition (VNMMP, 2011), with the maximum salinity of 20 ppt occurring at 21 km upstream of the river mouth and 6 ppt at 45 km upstream of the river mouth. In the high-flow season, on the other hand, the fresh water expands to the river mouth (Gagliano and McIntire, 1968; Thuy, 1988a, 1988b). The low gradient, up to 20 m thick subaqueous delta system, which is shown as a prominent subsurface reflector overlain by a thick clinoform that thinned offshore in the seismic profiles surrounding the modern Mekong River Delta, extends to < 30 m water depth in the coastal area. Late Holocene sediment thickness of the subaqueous delta is between 10 and 20 m (Xue et al., 2010).

The lower Song Hau channel is strongly influenced by tides. The tidal system is characterized as mixed semi-diurnal and diurnal tides, with a strong diurnal inequality (Thuy, 1979, 1988a, 1988b). The tides also have a remarkable asymmetry pattern such that the duration of flood tide is much shorter than that of the ebb tide. Maximum tidal range at the river mouth is ~3.5 m, and the average tidal range is ~2.2 m (Thuy, 1979). In the low-flow season, the maximum tidal range is ~2 m at Can Tho (Fig. 1), located ~90 km upstream of the river mouth, and ~0.5 m at Chau Doc (Fig. 1A), located ~230 km upstream of the river mouth. In the high-flow season, the tidal range is ~0.7 m at Can