Continental Shelf Research 147 (2017) 27–37

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Implications of tidally-varying bed stress and intermittent estuarine stratification on fine-sediment dynamics through the Mekong's tidal river to estuarine reach

R.L. McLachlan[a,*], A.S. Ogston[a], M.A. Allison[b,c]

[a] University of Washington, School of Oceanography, Seattle, WA, USA
[b] The Water Institute of the Gulf, Baton Rouge, LA, USA
[c] Tulane University, Department of Earth and Environmental Sciences, New Orleans, LA, USA

ARTICLE INFO

Keywords:
Mekong River
Mekong Delta
Tidal river
Estuary
Sediment transport
Aggregation
Morphology

ABSTRACT

River gauging stations are often located upriver of tidal propagation where sediment transport processes and storage are impacted by widely varying ratios of marine to freshwater influence. These impacts are not yet thoroughly understood. Therefore, sediment fluxes measured at these stations may not be suitable for predicting changes to coastal morphology. To characterize sediment transport dynamics in this understudied zone, flow velocity, salinity, and suspended-sediment properties (concentration, size, and settling velocity) were measured within the tidal Sông Hậu distributary of the lower Mekong River, Vietnam. Fine-sediment aggregation, settling, and trapping rates were promoted by seasonal and tidal fluctuations in near-bed shear stress as well as the intermittent presence of a salt wedge and estuary turbidity maximum. Beginning in the tidal river, fine-grained particles were aggregated in freshwater. Then, in the interface zone between the tidal river and estuary, impeded near-bed shear stress and particle flux convergence promoted settling and trapping. Finally, in the estuary, sediment retention was further encouraged by stratification and estuarine circulation which protected the bed against particle resuspension and enhanced particle aggregation. These patterns promote mud export ($\sim$1.7 t s^{-1}) from the entire study area in the high-discharge season when fluvial processes dominate and mud import ($\sim$0.25 t s^{-1}) into the estuary and interface zone in the low-discharge season when estuarine processes dominate. Within the lower region of the distributaries, morphological change in the form of channel abandonment was found to be promoted within minor distributaries by feedbacks between channel depth, vertical mixing, and aggregate trapping. In effect, this field study sheds light on the sediment trapping capabilities of the tidal river – estuary interface zone, a relatively understudied region upstream of where traditional concepts place sites of deposition, and predicts how fine-sediment dynamics and morphology of large tropical deltas such as the Mekong will respond to changing fluvial and marine influences in the future.

1. Introduction

1.1. Background

Rivers are the primary connection between land and sea, as they supply the bulk of particulate matter to the world ocean (Milliman and Meade, 1983). Although exploration of sediment pathways is traditionally split into distinct sections (i.e., fluvial, littoral, shelf), freshwater rivers seamlessly transition into intertidal and brackish areas. In large, low-gradient rivers, the tidally influenced freshwater section, herein referred to as the tidal river, can span hundreds of kilometers, as in the Amazon (Uncles et al., 2002), Yangtze (Zhang et al., 2012), and Mekong (Mekong River Commission Data Portal, MRCDP, accessed 2015) rivers.

Today, rivers are estimated to deliver around 13 Gt yr^{-1} of sediment to the ocean (Syvitski and Kettner, 2011). However, this estimate is based on gauges that typically lie upriver of tidal influence and do not account for vast regions that likely play a large role in the sediment-transport system, including tidal rivers and estuaries (Hoitink and Jay, 2016; Milliman and Farnsworth, 2011). The hydrodynamic and sedimentary processes in these transitional environments remain poorly understood, particularly within the tidal river and the approach of the tidal river into the zone of estuarine mixing, herein referred to as the tidal river - estuary interface. Thus, sediment flux magnitude and

* Correspondence to: University of Washington, School of Oceanography, Box 357940, Seattle, WA 98195, USA.
E-mail addresses: mclachlan.rl@gmail.com (R.L. McLachlan), ogston@uw.edu (A.S. Ogston), meadallison@tulane.edu (M.A. Allison).

http://dx.doi.org/10.1016/j.csr.2017.07.014
Received 3 October 2016; Received in revised form 13 July 2017; Accepted 31 July 2017
Available online 01 August 2017

timing as well as local morphological changes are difficult to characterize. This gap in knowledge raises the questions: *in what ways are sediment transport pathways affected within the tidal river to estuarine reach of distributaries?* and *how do these pathways alter channel morphology?*

Within estuaries, competition between river and tidal flows, with the former promoting stratification and latter providing mixing (Geyer and MacCready, 2014), produces changes in estuarine regime and sediment dynamics. These changes range from long-term climate shifts (e.g., Robins et al., 2016) to seasonal discharge fluctuations (e.g., Gensac et al., 2016; Nowacki et al., 2015; Wolanski et al., 2006; Woodruff et al., 2001) to daily spring-neap tidal cycles (e.g., Ralston et al., 2008, 2012). Present research has emphasized characterizing these shifts in discrete regions, separating the river from the estuary. However, relatively little attention has been given to controls on sediment flux patterns where tidal rivers transition to estuaries.

This study takes the innovative approach of analyzing how these factors interact and control sediment transport and channel morphology, linking near-bed shear stress (τ) and fine-grained particle aggregation to sediment resuspension and deposition throughout the range of fluvial and marine processes within a large tropical delta. Processes within the tidal river and estuary are individually addressed. Then, interactions of processes within the newly defined tidal river – estuary interface are examined and channel morphology feedbacks on distributary development are inferred.

1.2. Study region

The Mekong River spans > 4000 km from the Tibetan Plateau to southern Vietnam before reaching the East Sea, also called the South China Sea (Fig. 1). Estimated water discharge is 550 $km^3\ yr^{-1}$ and sediment discharge is ~150 $Mt\ yr^{-1}$ (Milliman and Farnsworth, 2011; Ta et al., 2002). Near the Cambodia-Vietnam border, the river splits into the Sông Hậu and Sông Tien. The Sông Tien repeatedly bifurcates, but the Sông Hậu remains a single channel until splitting around a mid-channel island called Cù Lao Dung. This paper focuses on the Sông Hậu, which carries over 40% of the total water flow (Nguyen et al., 2008), and its distributaries, the Định An and Trần Đề.

The Mekong Delta is presently tide-dominated (Ta et al., 2002) with mixed-semidiurnal, mesoscale tides. Tidal ranges attenuate from ~3 m at the mouth to 1 m at the Cambodian border, ~190 km upriver (MRCDP, accessed 2015).

Discharge is largely dictated by seasonal monsoons (Fig. 1). The wet summer monsoon (May to October) comes from the southwest and brings relatively weak winds and offshore waves. During this high-flow season, a stratified salt wedge propagates ~20 km upriver and ebb tidal currents dominate throughout the study region (Nowacki et al., 2015). The drier winter monsoon (November to March) brings much stronger winds and waves from the northeast (Hu et al., 2000; Nardin et al., 2016a). During this low-flow season, flood tides dominate a partially-mixed estuary that penetrates ~50 km upriver (Nowacki et al., 2015; Wolanski et al., 1996, 1998).

The lower tidal river has straight, seaward-shallowing channels (Gugliotta et al., 2017). Bed sediment is predominately sand and silt in the high-flow season and is capped by mud in the low-flow season (Allison et al., 2017; Nowacki et al., 2015; Wolanski et al., 1998, 1996). Nowacki et al. (2015) measured a net sediment export of 1 $t\ s^{-1}$ during high flow (2012) and a net import of 0.3 $t\ s^{-1}$ during low flow (2013) in the Định An channel, the larger of the two distributaries. During high flow, sediment is discharged from distributaries and deposited on the inner shelf (Eidam et al., 2017; Thanh et al., 2017) and along northern coastlines (Tamura et al., 2010). Energetic conditions during low flow erode this material (Thanh et al., 2017) and transport it onshore (Eidam et al., 2017; Fricke et al., 2017) and southwestward (Tamura et al., 2010), creating the oblong shape of the delta (Ta et al., 2002) and linking fluvial sediment flux to offshore sediment availability and coastline stability. By these processes, the Mekong Delta has been prograding for ~3.5 kyr (Ta et al., 2002).

The stability of the seaward margin of Cù Lao Dung is reliant upon fluvial sediment supply and the presence of mangrove forests (Bryan et al., 2017; Bullock et al., 2017; Mullarney et al., 2017; Norris et al., 2017), which often dominate tropical coastlines and stabilize substrate with unique root structures that trap sediment (van Maanen et al., 2015). Other studies in the area show that mangrove density and robustness are correlated with seasonal transport direction and sediment size (Nardin et al., 2016a, 2016b) and that shoreline propagation rates are dependent on river sediment load (Fricke et al., 2017).

The delta is rapidly changing due to natural and anthropogenic alterations. Numerous dams decrease flow variability (Xue et al., 2011) and reduce course-grained sediment flux (Kummu and Varis, 2007). Shifting tropical cyclone climatology may also be decreasing sediment

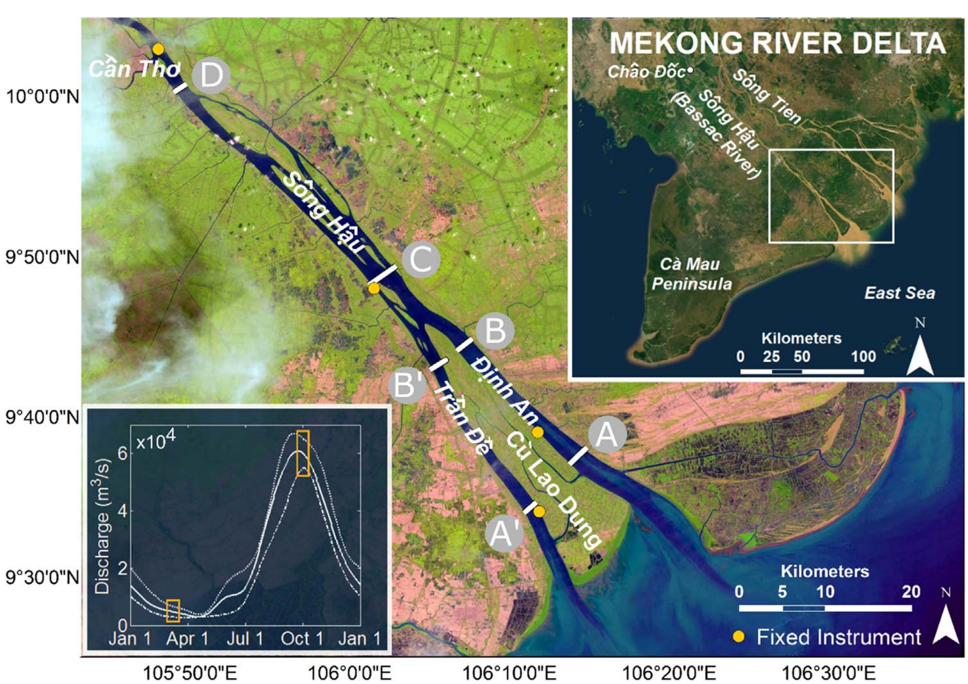

Fig. 1. Study area basemap with Landsat 7 ETM imagery acquired 25 September 2015. White lines on basemap delineate transect locations. Yellow dots show locations of fixed sensors deployed during data acquisition. Top right inset map displays the broader Mekong Delta (ArcGIS Basemap). Bottom left inset map displays the hydrograph (average maximum, mean, and minimum water discharge from 1960 to 2009) at Châu Đốc, about 100 km upriver of Cần Thơ. Discharge data was acquired from the MRCDP, accessed 2015. Orange boxes denote periods of data collection in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).