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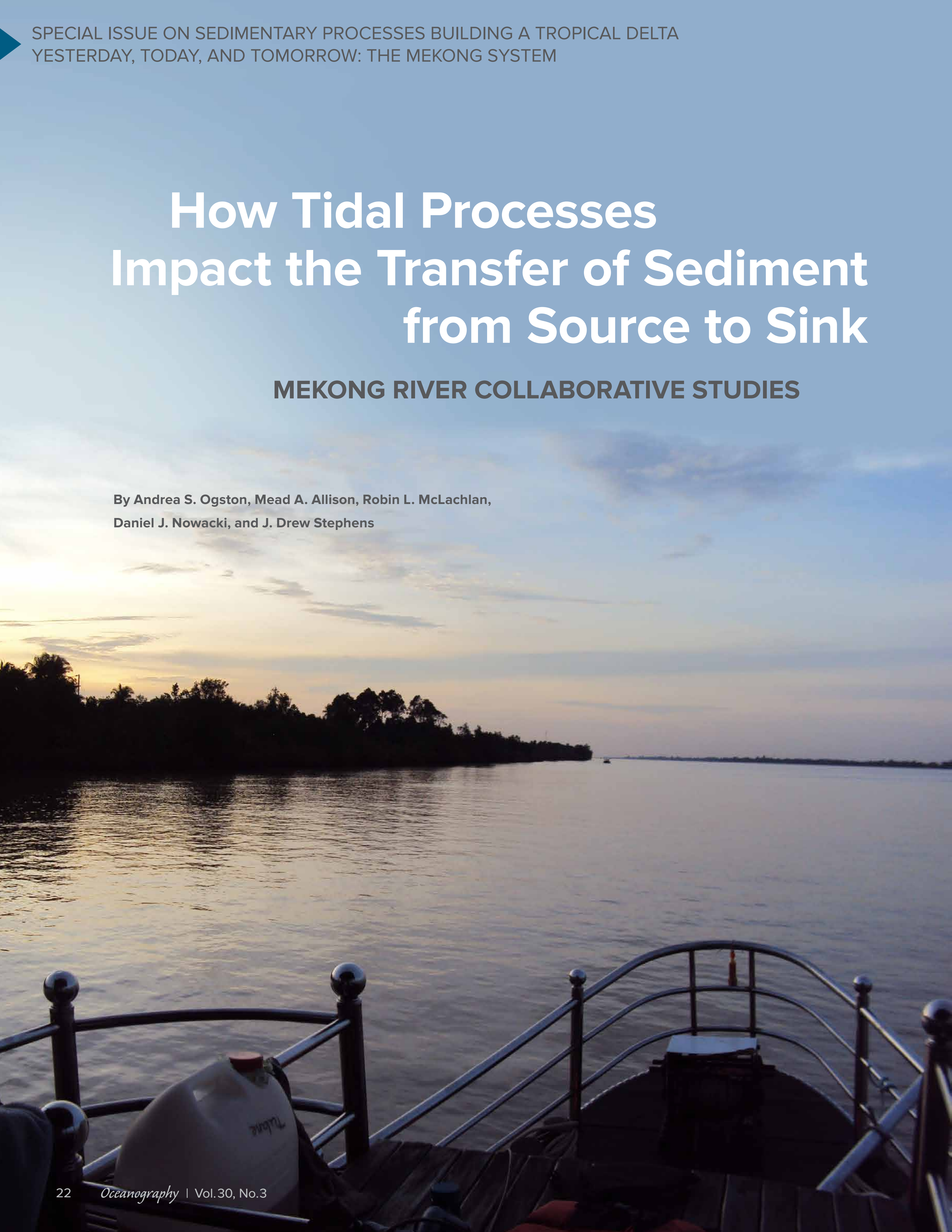


How Tidal Processes Impact the Transfer of Sediment from Source to Sink

MEKONG RIVER COLLABORATIVE STUDIES

By Andrea S. Ogston, Mead A. Allison, Robin L. McLachlan,
Daniel J. Nowacki, and J. Drew Stephens

ABSTRACT. Significant sediment transformation and trapping occur along the tidal and estuarine reaches of large rivers, complicating sediment source signals transmitted to the coastal ocean. The collaborative Mekong Tropical Delta Study explored the tidally influenced portion of the Mekong River to investigate processes that impact mud- and sand-sized sediment transport and deposition associated with varying fluvial and marine influences. Researchers participating in this 2014–2015 project found that as sand and mud progress down the tidal portion of the river, sands in suspension can settle during reduced or slack flows as river discharge becomes progressively more affected by tides in the seaward direction. Consequently, deposits on the tidal river bed are connected to sand transport in the channel. In contrast, fine mud particles remain in suspension until they reach an interface zone where waters are still fresh, but the downstream saline estuary nonetheless impacts the flows. In this interface zone, as within the estuary, fine particles tend to settle, draping the sand beds with mud and limiting the connection between the bed and suspended sand. In the Mekong system, the interface and estuarine zones migrate along the distributary channels seasonally, resulting in variable trapping dynamics and channel bed texture. Therefore, the signature of fluvial-sediment discharge is altered on its path to the coastal ocean, and the disconnected mud and sand supply functions at the river mouth should result in distinct offshore depositional signatures.

INTRODUCTION

Rivers are the largest suppliers of particulate material to the world ocean, and they are estimated to deliver ~13 Gt yr^{-1} today (~15–17 Gt yr^{-1} naturally prior to major dam installation; Syvitski and Kettner, 2011). Of this amount, the world's largest rivers discharge a disproportionate volume of sediment to the deltas of the world. Subaerial deltaic regions associated with large rivers tend to form near their land-sea boundaries from sediment delivered by the rivers. Deposition results from river deceleration associated with flatter terrain and declining water surface slopes. Vast human populations inhabit these low-lying plains, harvesting rich native fisheries and utilizing large areas for aquaculture and agriculture in the fertile river-delivered soils. Subtle climate variability and resulting sea level rise, as well as land use alterations and damming in the drainage basin, alter the ability of these deltaic regions to support ever-expanding populations. In order to manage and maintain the subaerial deltaic plains that result from the interplay of riverine (or fluvial) and marine processes, it is increasingly important to understand the dynamics that supply freshwater and sediment to and through these expansive lowland reaches.

Not traditionally belonging to the research realm of river geomorphologists or of estuarine/coastal oceanographers, the tidal river has generally been an understudied part of the source-to-sink sedimentary system. A significant amount of sediment may be trapped within this gateway region. In large, tropical systems, tidal rivers can stretch over hundreds of kilometers due to the broad, relatively low-lying coastal plains they transit. Some studies suggest that as much as one-third of the sediment load carried seaward by these rivers may be trapped within the tidal rivers (e.g., Ganges-Brahmaputra: Goodbred and Kuehl, 1999; Amazon: Nittrouer et al., 1995) through accumulation in tidal floodplains, or even by channel aggradation. Given the tremendous sediment transformation and trapping that may occur in tidal rivers, studies that examine the environmental components, hydrodynamic processes, and sediment dynamics are critically needed within this region to better understand the full source-to-sink system.

The tidal Mekong River (Figure 1) is an excellent place to study mud- and sand-sized sediment dynamics in a tidal river and estuary and to explore the evolution of channel morphology. The large tide-dominated Mekong Delta is characterized by a network of tidal distributary channels surrounded by low-lying vegetated floodplains where agricultural practices control inundation. The Mekong River can be divided into five sections. The freshwater river (fluvial end member) extends from the headwaters to >300 km from the ocean and is not affected by tides or other ocean processes. The tidal river begins ~300 km from the ocean where the flows become affected by tidal processes that increase in intensity approaching the river mouth. Next comes an intermediate section called the interface, which occurs within the tidal river but upstream of where the river converges with saline ocean waters; it is influenced by the downstream estuary where fresh- and saltwater mix. At most, the estuary can penetrate ~40–50 km into the distributaries. Finally, brackish and/or riverine waters discharge into the ocean, referred to as the marine end member of the system. Thus, between the fluvial and coastal-marine end members lie the tidal river, the interface, and the estuary over which sedimentary signals are altered.

For any individual river, the sediment load reaching the ocean is typically estimated from information obtained at the lowermost river gauging station, which is almost always upstream of tidal influence. For the major rivers of the world, the tidal river can extend inland for hundreds of kilometers. Thus, the hydrodynamic and sedimentary processes in these long tidal sections of river remain poorly understood. As particles transit downstream along a deltaic distributary channel, they are subject to changing water flows: from steady unidirectional, to tidally unsteady, to tidally reversing, and ultimately to estuarine mixing. Along the majority of this continuum, knowledge is lacking about how the pathways and processes of mud and sand transport evolve.

The collaborative 2014–2015 Mekong Tropical Delta Study (and preliminary studies in 2012–2013) provided an unprecedented opportunity to focus on sediment dispersal in a tidal river and its intertidal flanks, shoreline deposits

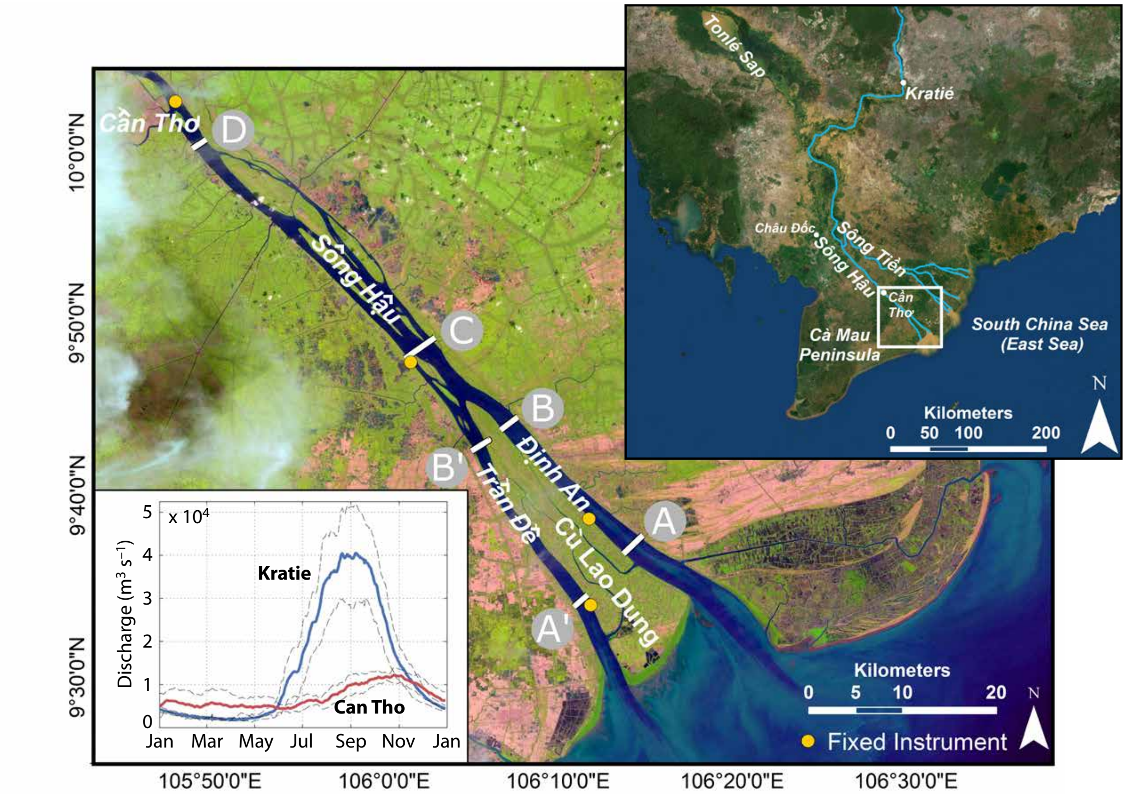


FIGURE 1. Lower tidal portion of the Mekong River, site of distributary channel investigations that were part of the 2014–2015 Mekong Tropical Delta Study. The river starts to bifurcate downstream of Kratie, Cambodia, breaking into seven distributaries. The two largest are the Song Hau and the Song Tien. This article focuses on the Song Hau, which is reported to carry ~40% of the total Mekong water discharge (Nguyen et al., 2008). Note that tides propagate up ~300 km upstream of the river's mouth, but saline marine waters only reach ~40 km upstream. Discharge data shown are the historical average (± one standard deviation; dashed lines) based on 45 years of data at Kratie and seven years at Can Tho (inset after Nowacki et al., 2015).

colonized by mangroves, and linkages with shallow deposits on the continental shelf. Additionally, these studies permitted an assessment of the role that climate and human impacts, such as sea level rise and damming of the upper river, play on sediment dynamics.

Our goals have been to identify and quantify the range of dynamical processes along the river-to-ocean progression described above. Understanding these processes allows a better conceptualization of the formation and evolution of deltaic distributary channels, and of prograding/eroding channel islands in reaches where there are multiple channel courses. The controls within the tidal river alter the magnitude and timing of the fluvial-sediment supply signal before discharge to the continental shelf. Where deltaic deposits are formed either at the shoreline or in subaqueous environments, tidal river influences should be detectable in the signatures of sediment flux and deposition found there.

In this paper, we first summarize the characteristics at the ends of the system—the fluvial and marine components. We then discuss the processes within the tidal river and estuary that form the pathways and sinks for sediment and that determine the bed morphology of the distributary channels. Finally, we discuss possible Mekong distributary evolution based on these processes.

TWO ENDS OF THE MEKONG RIVER SYSTEM

The Fluvial End Member

The Mekong River originates on the Tibetan Plateau of China, where it derives much of its sediment load of ~160 × 10^6 t yr^{-1}, as estimated at Phnom Penh, Cambodia, 300 km upstream of the mouth (Milliman and Meade, 1983). The lower river basin and Mekong Delta are located in a wet tropical setting (~8.5°N–10.5°N), where the system receives ~80% of its precipitation in May through September during the southwest monsoons (Mekong River Commission, 2005). At the Kratie gauging station, 500 km upstream of the mouth, river discharge reaches its maximum in August–September and its minimum in March–April (Figure 1). This seasonal water discharge is modified by Tonle Sap lake, which acts as a natural flow capacitor, smoothing out seasonal variability at locations downstream (see delay in discharge peak between Can Tho and Kratie, Cambodia, in Figure 1). At high flow, freshwater extends to the mouths of the distributary channels, but during low flow, saltwater penetrates ~40–50 km up river (Wolanski et al., 1996, 1998;

Nowacki et al., 2015).

Suspended sediment loads at Kratie, the gauging station located upstream of the delta, have been recently re-evaluated and are estimated to fall in the range of 80–110 Mt yr^{-1} (Milliman and Farnsworth, 2011), with recent data suggesting that the lower limit may be more appropriate (Darby et al., 2016). The sediment load at Kratie is highly seasonal, with little appreciable load from January to June. These estimates are made above the bifurcation of the river into distributary channels and at a location hundreds of kilometers upstream of the river mouth that has little to no influence from tidal processes and therefore may have little connection to the sediment discharge patterns and fluxes at the entrance to the coastal ocean.

There has been considerable concern about the influence of anthropogenic activities on the sediment load delivered to the delta, specifically focused on sediment limitation resulting from upstream damming and sand mining in the deltaic distributary channels. Furthermore, Darby et al. (2016) report that changes to climate patterns, including a changing tropical cyclone climatology, have drastically reduced the amount of suspended sediment leaving the fluvial system. In all, the absolute amount of sediment leaving the purely fluvial end member as suspended load is not well established, yet recent studies suggest that it has been reduced on the order of 25% over the past 25 years (Kummu et al., 2010; Kondolf et al., 2014).

The Marine End Member

At the marine end of the tidal river, oceanic processes drive fluctuations in river discharge and carrying capacity that impact the sediment delivery through this reach. The coastal water levels at the mouth of the Mekong River exhibit mesotidal fluctuations, with semidiurnal ranges during spring tides of ~3.5 m at the ocean boundary, decreasing to ~2.0 m at 90 km upstream (Can Tho) and to ~1.0 m at 190 km upstream (Mekong River Commission, 2005). Offshore, sedimentary processes are further affected by seasonal wind and wave activity and by circulation driven by buoyant discharge at the coast (e.g., Eidam et al., in press). Seaward of the mouth of the largest Mekong distributary, the Song Hau (also known as the Bassac River), seasonal monsoon systems dictate wave and current properties. The rainy (southwest) monsoon (May–September) generally exhibits lighter winds, resulting in slow currents toward the northeast. The windy and dry (northeast) monsoon (October–April) is characterized by strong alongshore trade winds, persistent wave activity with associated sediment resuspension, and coastal currents toward the southwest.

Not only is the marine end member the recipient of the fluvial discharge signal, there is also the potential for sediment previously debouched to the shelf to be imported into distributary channels during reduced river flow (Nowacki et al., 2015). Accordingly, offshore processes need to be considered for a full understanding of the sediment source function at the mouth. In large river systems, understanding the linkages between the tidal river, the estuary, and offshore environments is necessary to conceptualize the deltaic processes on time scales of hours to millennia.

PROCESSES WITHIN THE TIDAL RIVER AND ESTUARY

There is significant potential for sediment entrapment in the tidal river and estuary, which would affect the amount and timing of sediment discharge to the ocean as well as permit deposition along the channel bed. In these zones, mud- and sand-grained sediments appear to follow different pathways, as the deceleration and acceleration of the tidal flows segregate particles by settling velocity. Between the fluvial- and marine-dominated end-member states, sediment dynamics vary due to fluctuating magnitudes of fluvial and marine influences in the tidal river. In this section, we discuss the processes affecting both mud- and sand-sized sediment along the region and channel morphologies resulting from these processes.

Pathways and Sinks of Fine-Grained Sediment

We focused our investigations on the Song Hau distributary of the Mekong River, where prior studies suggested that salinity intruded into the lower ~50 km of the distributary during seasonal low-river flows, and was confined near the mouth during high river flows (Wolanski et al., 1996, 1998). During high-flow conditions, Wolanski et al. (1996) observed a salt-wedge estuary and sediment export to the ocean. Ebb flows (tide plus river flow) were stronger than flood flows (tides minus river flow), the river bed was mostly sandy, and no along-channel gradient in suspended sediment concentration was observed. A near-bed maximum in turbidity was present, known as the estuarine turbidity maximum, which is seen in many estuarine systems. During low-flow conditions, Wolanski et al. (1998) found the Mekong estuary to be partially mixed, with stronger peak flood flows than ebb flows. Suspended sediment, potentially deposited on the inner shelf during a previous high-flow period, may have been transported back from coastal waters into the river mouth and trapped by estuarine processes.

The seasonal experiments conducted in the Mekong tidal river as part of our collaborative international program in 2014–2015, including preliminary studies in 2012–2013, were designed to further explore the range of transport and deposition processes not only in the estuary but also in the upstream tidal river reach. We emphasized a dynamical understanding of transport processes, including evaluation of bed stresses (the stress induced on the channel bed sediment by the flows above it) and resuspension of distinct sand and mud populations, and we focused on the connections between the transport dynamics and the channel bed. These studies within the tidal Mekong River focused on the lower

80 km of the Song Hau from the city of Can Tho to the mouth, where flows are discharged into the East Sea (also known as the South China Sea). The Song Hau is the largest distributary channel and carries ~40% of the water discharge of the Mekong (Nguyen et al., 2008). Within the Song Hau distributary, water discharge fluctuates (and reverses at the seaward end) with the tide: the discharge variation is seasonally most asymmetric at high river discharge with flood and ebb discharge rates and duration out of balance over the tidal cycle (Figure 2), and spatially becomes increasingly asymmetric with distance upstream. Overall, we found that tidal discharge fluctuations (Figure 3) in the river, along with the periodic presence of an estuarine turbidity maximum, influence movement of salt and fine-grained sediment through the system. This results from variations in bed stress, particle aggregation (flocculation), settling, and trapping of sediment within the distributary channel.

The flow and sediment dynamics of the tidal Mekong River undergo a comprehensive seasonal regime change between high and low river discharge. This change is highlighted at the downstream limit by the seasonal transition from a tidal freshwater system with an ephemeral salt wedge to a partially mixed estuarine system (Figure 4; Nowacki et al., 2015). During high river discharge, estuarine mixing generally occurs outside the river mouth, and the salt wedge penetrates the distributary channel mouths only during a short phase of the tide. As a result, fine-grained sediment is exported when river discharge is high. Residual sediment flux is seaward throughout the water column during high flow. Decomposition of sediment flux terms shows that during high flow, over 80% of the total sediment flux could be attributed to advection by the river, with most of the remainder contained in the tidal term, which encompasses processes such as tidal pumping and local resuspension and deposition. In contrast, during low flow, the seaward portions of distributaries become partially mixed estuaries, the net flux is inland, and sediment is imported from the offshore regime. The flux decomposition demonstrates that the transport is primarily associated with estuarine exchange and tidal processes (e.g., tidal pumping, resuspension) and the river term is generally found to be unimportant. Baroclinic and tidal processes, especially local resuspension, are more important during low flow. The resulting residual sediment flux is landward in deep regions and seaward in the upper water column.

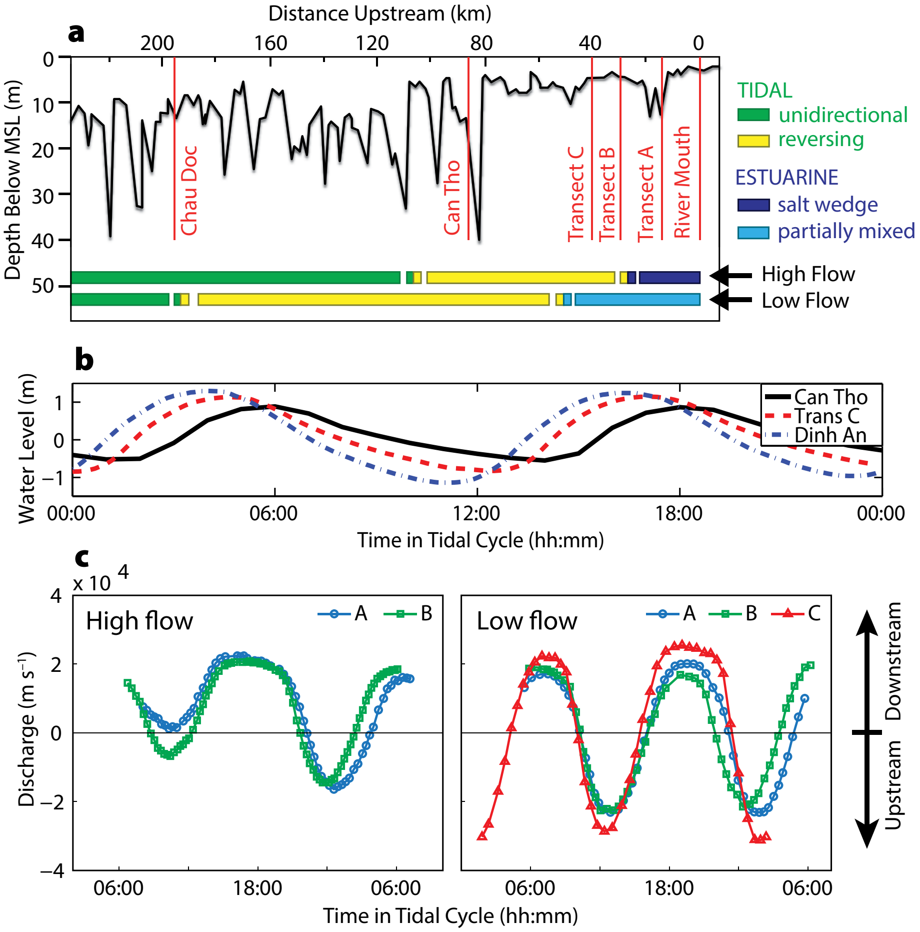


FIGURE 2. (a) Along-channel characteristics of the Song Hau distributary, including depth and tidal/estuarine influences. The distributary channel is considered a tidal river upstream of the mouth to locations above Chau Doc. (b) Water surface variations relative to the mean water level under high discharge conditions, illustrating the attenuation of the tidal range and progressive asymmetry. *After McLachlan et al. (in press)* (c) Mekong River discharge under high and low river discharge conditions at transects shown in Figure 1. Note that discharge at Transect C is larger than at A and B due to the bifurcation in the distributary channel. *After Nowacki et al. (2015)*

The freshwater tidal zone upstream of the estuary is of particular interest because processes there, such as bed shear stress, are impacted by downstream stratified flow dynamics in the area we refer to as the interface zone (McLachlan et al., in press; Figure 4b). Convergence of fine-grained sediment is enhanced due to the slower flows and reduced bed stresses in this region as well as in the estuary, promoting settling and deposition. In addition, particles that had aggregated in the salt front when the estuary was located at its landward maximum within the tidal cycle continue to be available for resuspension in freshwater when the estuary retreats on ebb flows. Thus, although estuarine processes are understood to be important drivers of flow convergence (Nowacki et al., 2015), the Mekong studies also identified the interface region as an important processing area for sediment prior to introduction into the region classically considered estuarine.

In addition, changes in fine-grained particle characteristics and settling velocity affect the ability of tidal and fluvial processes to maintain sediment in suspension through the interface and estuarine reaches. In this large tropical river, some of the fine particles transit the tidally influenced reach as flocs, or aggregated particles. Flocculation occurs within the freshwater of the tidal river upstream of the saline limit in the distributary, and flocs are particularly evident during low-flow conditions. Camera analysis of sediment in suspension shows the fine-grained fraction has a flocculated component during low discharge at Can Tho where no salt is ever seen but where reversing tidal flows are observed. Flocs in the freshwater reach of the tidal river can have diameters of >200 microns (McLachlan et al., in press), and aggregation is likely enabled by natural organic coatings (Figure 5). The amount and size of flocculated particles in the surface water remain relatively uniform downstream through the Dinh An subchannel of the Song Hau distributary channel, where salt is present in high concentrations at depth but is not typically well mixed throughout the water column. The aggregated fraction increases by ~25% in the Tran De subchannel relative to that in the Dinh An subchannel during low flow because vertically mixed salinity supports inter-particle bonding.

The regime change that takes place in the tidal Mekong River has important implications for suspended sediment import and export to/from the estuary and interface region. During high flow, the Song Hau is estimated to export sediment to the shelf at a rate of ~1.7 t s^{-1} (Nowacki et al., 2015), with the Dinh An subchannel, the largest of the two subchannels, being responsible for about ~60% of the total sediment flux (Nowacki et al., 2015; McLachlan et al., in press). During low flow, the Song Hau imports sediment from offshore at about 0.25 t s^{-1}, with most of it traveling through the smaller Tran De subchannel. The presence of a large mid-channel island at the river mouth influences the spatial distribution and transport pathways of sediment and salt, with flow in the Tran De subchannel exhibiting more convergent flow, priming conditions for particle deposition. Applying some simple assumptions about yearly river flow patterns yields an annual Dinh An subchannel suspended sediment discharge of ~9 Mt yr^{-1}. Upscaling this value to estimate the overall rate for the Mekong River, we suggest that sediment discharge at the distributary mouths is ~40 Mt yr^{-1} (Nowacki et al., 2015), a value lower than that found in earlier studies by Harden and Sundborg (1992) and Milliman and Farnsworth (2011) but comparable to the recent Darby et al. (2016) estimate.

Seasonal flow and sediment transport dynamics through the distributary channels are reflected in channel bed grain size characteristics. As a result, solely based on water column dynamics, we can assume that bed grain size would be coarser during high flow and finer during low flow, and that imported mud to the Tran De subchannel would lead to considerable mud deposition. Bottom mapping and sampling of the reversing tidal and estuarine portion of the Song Hau distributary channel in high- and low-discharge conditions confirm this (Nowacki et al., 2015; Allison et al., in press), and allow us to further examine these impacts.

The Pathways and Sources of Sand-Sized Sediment

Although on a global basis the majority of sediment export to the coastal marine environment is made up of mud-sized particles (<63 µm), sand (63–2,000 µm) is an important component of the structure and maintenance of deltas. Thus, its delivery in times of sea level change and human-caused supply interruption is critical to maintaining the health of the delta and of those who live upon it. Sand may transit the tidal river continuum either as bedload or suspended load according to the strength of the ebb and flood currents within the tidal river and estuary. In the Mekong River, sand-sized material was found to be a significant component

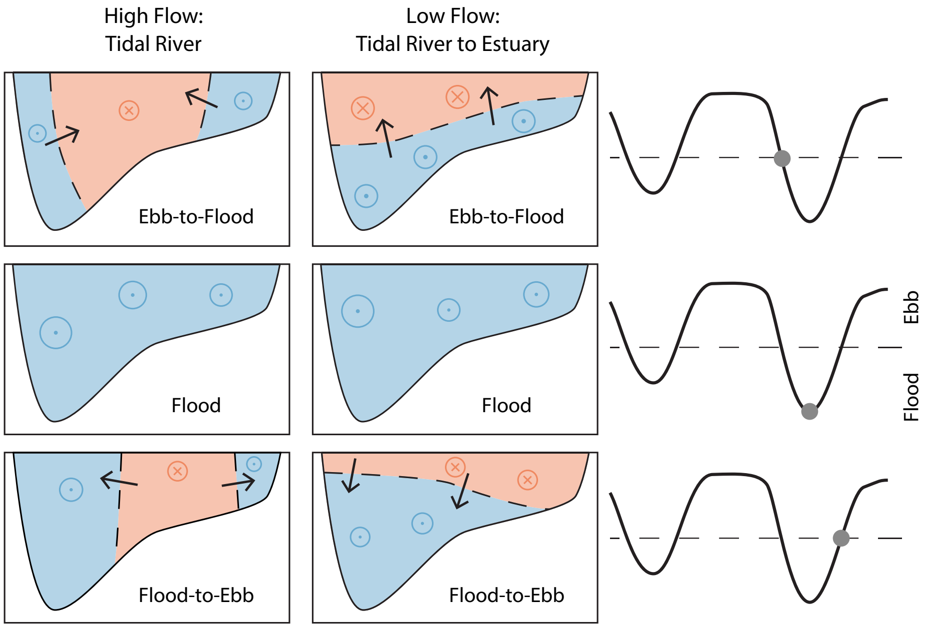


FIGURE 3. Sections of water velocity across Transect B in Figure 1 at three tidal phases (red regions represent downstream flow and blue regions upstream flow). Under high-flow conditions, when Transect B is upstream of estuarine processes, the flows are not solely influenced by the topography at the specific cross section but are also influenced by the downstream saline wedge and channel morphology near the mouth. Under low-flow conditions, when Transect B is within the estuary, lateral variations in flow across the transect suggest local control with flood flows initiating near bed across the transect, and ebb flows initiating at the surface over the shallows.

of the total suspended sediment export to the coastal ocean, and may represent 5%–20% of the modern estimates of suspended sediment export (Stephens et al., in press). Sand transport processes change dramatically between the high- and low-discharge seasons in this system, and in a different manner than mud transport processes change. This difference creates a segregation of mud and sand pathways as both fractions progress down the tidal river and through the estuary. During the high-discharge season, suspended sand transport is controlled by complex relationships between bed material, tidal flow, distance upstream, and water discharge. With their rapid settling velocity, sand particles tend to fall out of suspension during the brief but regularly occurring slow/slack tidal flows when bed shear stress is at a minimum. During the low-discharge season, bed stresses peak at similar values as those in the high-discharge season because the tidally varying discharge values dominate the discharge signal, and yet suspended sand transport through the seaward segment of the tidal river is almost completely shut down. Correlation between sand fluxes and bed material suggests that this shut down is due to mud mantling of the channel floor, which restricts access to the local sand source in the channel beds (Allison et al., in press; McLachlan et al., in press; Stephens et al., in press). As the Tran De subchannel has a generally muddier bottom in all seasons, the larger Dinh An subchannel dominates sand transport.

Techniques typically used in fluvial environments to evaluate size-dependent sediment fluxes are challenging to use under tidally variable discharge conditions (see Box 1). However, Stephens et al. (in press) show that sand flux is generally related to the tidally varying discharge of the river (Figure 6). They use modeled river discharge conditions to estimate that a net value of 6.5 Mt yr^{-1} of sand may be exported from the sum of the Mekong's distributaries based on present conditions in the Mekong tidal

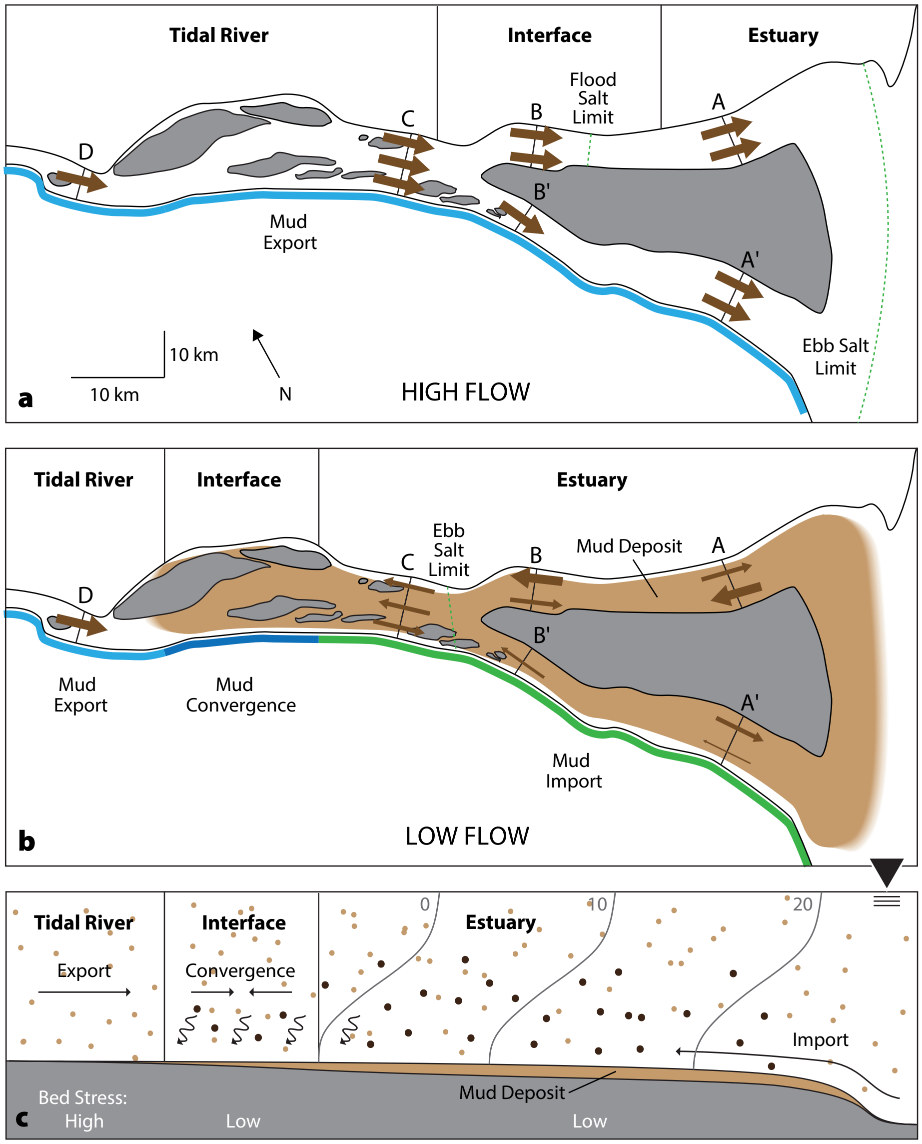


FIGURE 4. Conceptual diagram of sediment flux and bed character throughout the seaward reach of the Song Hau distributary. Within this reach, the hydrodynamic regime changes from acting mainly as a tidal river under (a) high-flow conditions, with estuarine processes only penetrating into the distributary channels during part of the tidal cycle, and (b) low-flow conditions, with a partially mixed estuary moving up and down the distributary channels at all tidal phases. The channel bed character reflects the convergent sediment fluxes within the tidal river, interface, and estuarine environments with a seasonal muddy drape covering relict or sand field deposits. This drape is represented in (c), which is a conceptual section of the lower distributary channel during low flow and which emphasizes the interface that occurs within the tidal river.

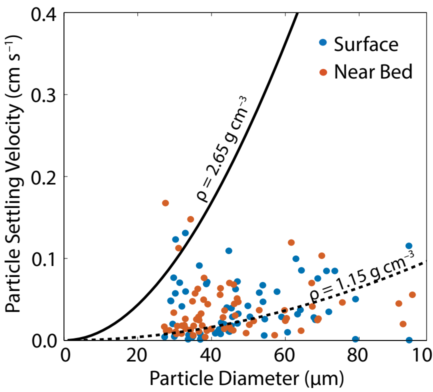


FIGURE 5. Particle size and settling velocity as obtained from a settling chamber. Although particles are likely somewhat disturbed prior to analysis, the general patterns show aggregated sediment in the tidal river upstream of the zone of estuarine influence where aggregation is predicted in association with the introduction of salts in the fluid. The effective density of the particles (dashed lines) suggests that, during low-flow conditions, most of the >40 µm particles are aggregates of relatively low density. *From McLachlan et al. (in press)*

BOX 1. SAMPLING ON THE LOWER MEKONG RIVER

Methodologies used for the Mekong Tropical Delta Study combined tools designed for both fluvial and marine research. The lower Song Hau is an extremely active transportation corridor. Boat traffic ranges from small individual fishing shells to large commercial container ships that continuously transit the waterways and thus make sampling on a rigid time schedule nearly impossible. We used a local boat, M/V *Mahogany Star*, a 20 m wooden vessel usually employed for tourism in the upstream distributaries. Our sampling strategy was to occupy transects at locations marked in Figure 1 for 24.8 hours (12.4 hours when tidal inequalities were at their minimum), and to transit continuously back and forth to develop sequential cross sections of physical water-column properties and sediment suspension. An acoustic Doppler current profiler (ADCP) ran continuously, and on every other crossing, we deployed a conductivity, temperature, depth, and turbidity profiler at two to four stations located across the transect. A laser in situ scatterometry and transmissometry (LISST) instrument was also attached to the profiling instrument package to provide information on particle size. At the four phases of tidal currents (max ebb, slack low, max flood, and slack high), water samples were collected using an isokinetic sampler (a fluvial tool) and a snapping Niskin-style bottle sampler (a coastal marine tool). The degree of aggregation was evaluated with a size-settling chamber.

During these transects, a pole-mounted multibeam system (a 400 kHz broadband echosounder) linked to a LiDAR system continuously mapped bathymetry and bankline morphology using motion correction. After multibeam and LiDAR soundings underwent quality control, and motion sensor and navigation data were merged, bathymetry and elevation grids of 1 × 1 m were created (Allison et al., in press).

Suspended sand fluxes were evaluated using data from LISST profiler casts during high discharge in September–October 2014. This volume concentration of a sand-size mode measured by the LISST was corrected for the presence of sand-size flocs using the isokinetic samples and converted to a mass concentration of suspended sand (see Stephens et al., in press, for methods). Multiple cast profiles were then integrated over depth and across the river channel to arrive at a suspended sand (mode) flux.

Total suspended sediment fluxes were evaluated at all seasonal conditions in the 2014–2015 experiments, as well as during preliminary field efforts in 2012–2013, using profiles of optical backscatter and ADCP transect data (Nowacki et al., 2015; McLachlan et al., in press). The backscatter profiles were calibrated with in situ water samples, which were filtered for mass concentration. These data were integrated with ADCP data, and spatially variable fluxes were evaluated over different phases of the tide. Cross-sectional discharge values were obtained by prescribing a no-slip condition at the bottom, fitting a shape-preserving spline to the empty regions, and net discharge evaluated by integrating time varying cross-sectional values over the 24.8-hour tidal cycle.

FIGURE B1. (a) M/V *Mahogany Star* was used to conduct channel studies during the 2014–2015 international study of the Mekong Delta. This image shows the pole-mounted ADCP and multibeam systems. (b) Some of the instruments used to evaluate the mud- and sand-sized sediment fluxes within the tidal river and estuary. The small CTD, the OBS (turbidity sensor), and the laser in situ scatterometry and transmissometry (LISST) profiling system are mounted together in a frame, and the isokinetic sampler is at right. (c) Some of the scientists and crew involved in the 2014–2015 studies are shown here gathered on the upper deck of M/V *Mahogany Star*.

river. Bedload was not a large contributor to net sand fluxes through the seaward reach of the tidal river, as evaluated by the translation of bedforms both in the upstream and downstream direction over the tidal cycle. Although the magnitude of net bedload flux is not great, sand that moves as bedload and maintains the observed bedform fields is easily drawn out of the bedload layer and maintained in suspension at slightly higher shear stresses. Therefore, the bedload is a critical connection between the sand source at the channel bed and the net export of sand.

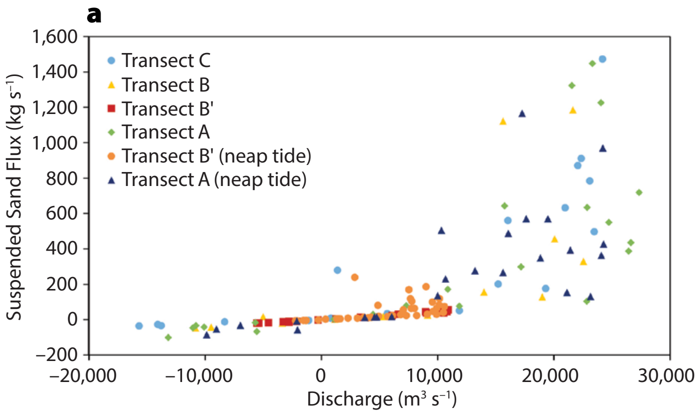
In contrast to the mud-sized sediment fluxes within the Mekong distributaries, sand may not re-enter the distributary channels due to: (1) estuarine processes that reduce bed shear stresses in the denser, more saline water layers, and (2) depositional processes that mantle the channel bed with mud, cutting off a sand source to the water column. The temporal sequencing of seasonal sand and mud fluxes to the coastal environment likely affects the development of the shoreline environments (see Mullarney et al., 2017, and Fagherazzi et al., 2017, both in this issue) and the subaqueous delta and stratigraphic structures found there (see Nittrouer et al., 2017, and Liu et al., 2017, both in this issue).

Morphology of Distributary Channels

Along the fluvial to tidal river to marine continuum, tidally modulated flows, tidally reversing flows, and/or estuarine dynamics affect the stresses at the bed and throughout the water column. Thus, they control the suspension of mud- and sand-sized sediment and the transport of bedload, which results in differing channel morphologies. For example, a study by Gugliotta et al. (in press) defines the varying morphologies along the length of the Mekong tidal river. Channels in the landward (non-reversing) tidal river exhibit downstream deepening, fining of bed sand sizes, and limited mud. Channels in the seaward reaches of the tidal river exhibit downstream shallowing, uniform sand sizes, and a significant proportion of mud. Large rivers, such as the Mekong with its long tidally influenced reach, allow us to investigate the range of along-channel variations in environments within the tidal river. Our studies as part of the international collaborations in 2014–2015 explored the seaward reaches of the tidal river to investigate the connections between seabed morphology, active transport, and net export of sand and mud.

We examined the Song Hau distributary environment where fluvial and marine influences are both important to the dynamics. The channel floor proved to be composed of three main channel bed facies—sandy dune fields, low-discharge deposits of soft muds, and substratum outcrops of relict facies (Figure 7; Allison et al., in press). Sandy bottoms, characterized in multibeam imagery by the presence of dunes, comprise ~19% of the channel floor during high discharge. These long ribbon-like deposits occur only in the cross-channel direction, are usually found on the margins of the thalweg (the path of the deepest points within a channel), and are generally composed of deposits less than a few meters thick, except as bar extensions of mid-channel islands that are a focus of sand mining activities. Above the island of Cu Lao Dung, which formed at the bifurcation of the Song Hau, more sandy substrate is found in shallower secondary channels of the main stem that parallel the deeper navigation channel (see Allison et al., 2017, in this issue). By comparing flow rates from modeling studies (Xing et al., in press), we deduce that these secondary channels have weaker residual flows that result in a reduction of sand throughput and a focus area for sand storage. As flow in the Song Hau separates into the Dinh An and Tran De subchannels around Cu Lao Dung, a larger area of the bed consists of sand along the more northerly Dinh An pathway to the ocean. This makes it the dominant pathway for the total load of sediment, and the preferred channel for the 6.5 Mt yr^{-1} estimated net sand export.

The majority (~80%) of the Song Hau channel floor in the study reach has little or no modern sediment, particularly during the high-discharge season, resulting in widespread evidence of substratum outcrops. These exposures take the form of steep-sided tabular and sidewall outcrops of resistant strata and furrowed pavements (Figure 7) that are laterally continuous for kilometers along channel. The furrows are composed of grooves incised into the substratum (and possibly thin modern mud cover) by directionally stable and intermittent tidal currents. The



b

Transect	Suspended Sand Flux (ton d^{-1})
C	29 x 10^3
B	22 x 10^3
B′	2 x 10^3
A	29 x 10^3

FIGURE 6. (a) Suspended sand flux in the Song Hau distributary channel as evaluated from laser in situ scatterometry and transmissometry profiler casts during high discharge in September–October 2014. The flux is plotted against the tidally varying river discharge (positive downstream, negative upstream) measured over cross sections using a boat-mounted ADCP (see Box 1) The results show the strong relationship between discharge and the mass of sand transported in suspension, indicating a local bottom source of resuspendable sand. Note the larger water discharges (up to ~25,000 m^3 s^{-1}) during ebbing tide when the river flow is additive with the tide. (b) The tidally averaged flux values at each transect during high river discharge.

extent of substratum exposure is greater than that observed in other systems such as the Mississippi River, which has a microtidal range. The exposure in the Song Hau may relate to a relatively limited sand supply from the catchment and/or efficient transfer of both sand and mud through the channels of the tidal river and estuarine reach. Comparison with stratigraphy in Mekong Delta borings collected adjacent to the Song Hau (Ta et al., 2002) suggests these substratum outcrops are mainly composed of delta-front and intertidal-to-subtidal-flat silty sands and sandy silts deposited since the delta began prograding seaward ~3,500 years ago. Erosion and degradation of these outcrops are apparent at present and are predicted to accelerate in the future due to relative sea level rise, sand mining, and dam-induced reduction in sediment supply from the catchment (Allison et al., 2017, in this issue). Thus, these outcrops may provide a source for sand to the littoral sand dispersal system and maintain the structure of the subaqueous delta into the future.

Modern soft mud layers cover large parts of the channel beds seasonally throughout the interface and estuarine regions of the tidal river (Figure 8). Mud layers are observed to form on the channel floor during the low-discharge season in deposits 0.25–1.0 m thick in the Dinh An and Tran De subchannels surrounding Cu Lao Dung. These layers mantle both substratum outcrops (e.g., furrows) and much of the exposed sand field; their role in the sand and mud dynamics is discussed above. Large areas of modern mud cover the Tran De beds and are indicative of the enhanced fine-grained sediment trapping and deposition there.

The Song Hau and the other distributary channels of the Mekong River are vital as navigation arteries for transporting goods to and from the rapidly growing cities in the delta, and they are a vital source of sand for construction purposes (Brunier et al., 2014). These channels now also serve as trunks for a vast array of artificial side channels used for irrigation and transportation in the delta. The expanding human footprint on the distributaries, as well as the likely alteration to the hydrograph and sediment delivery from the catchment (Allison et al., 2017, in this issue), means the future evolution of these channels will likely differ from their evolution during the last 3,500 years. Beginning ~1,300–1,400 years ago, the delta front has prograded while the channel location remained stable but extended through channel incision into late Holocene fluvio-deltaic deposits (e.g., Tamura et al., 2012). Competing processes make extrapolation into the future difficult. In one scenario, we might expect that sediment starvation and removal, as well as rising relative sea levels, will result in channel deepening by incision into deeper and older strata. This morphodynamic evolution of the channels likely would feedback into the timing and magnitude of sediment supplied to the shoreline (mangrove and other) and the subaqueous delta. But other dynamical factors such as vertical mixing and settling velocities are also at play; how might these play out in combination?

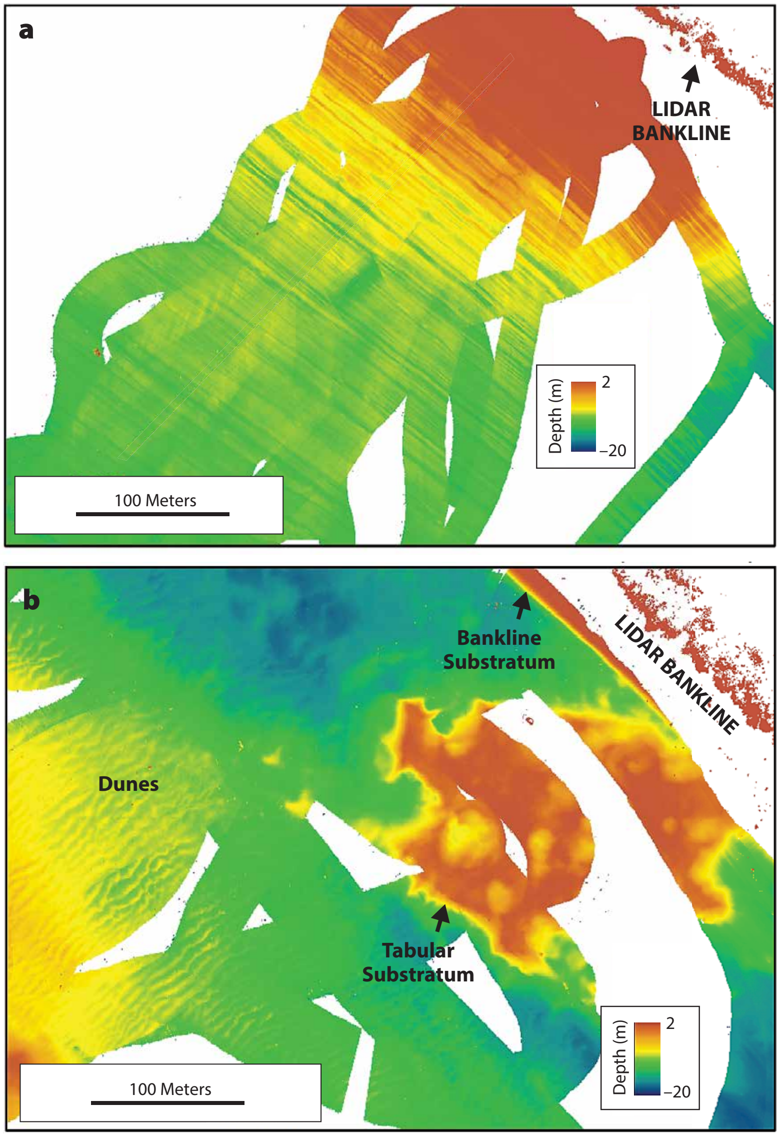


FIGURE 7. (a) Multibeam seafloor mosaic at Transect A in Figure 1 (Dinh An subchannel) in the 2014 high flow study showing longitudinal furrows along the left descending distributary channel bank. (b) Multibeam mosaic of Transect B in Figure 1 (also Dinh An subchannel, upstream of Transect A) in the high flow study showing a tabular bankline outcrop and mid-channel dunes. *After Allison et al. (in press)*

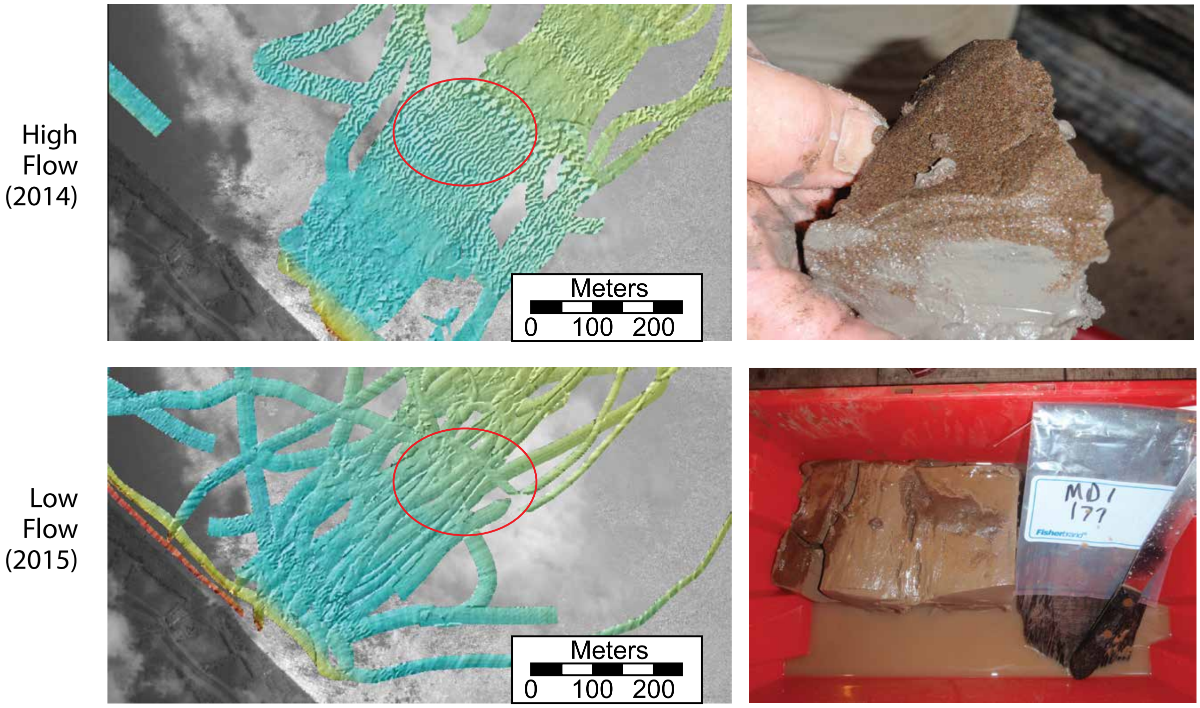


FIGURE 8. Multibeam bed surveys illustrating the change in channel beds between seasons. Under high-flow conditions in 2014, sand dunes are evident (see red circle) and bed-surface sediment samples show a coarse sand bed. Under low-flow conditions in 2015, no bed features are evident in the repeat survey (see red circle), and surface samples of soft mud were obtained.

MEKONG DISTRIBUTARY EVOLUTION

The sum of sediment fluxes from active sedimentary processes throughout the tidal river-to-estuary system leads to stability or instability of channel morphologies on a range of temporal scales. On the shortest seasonal scale, mud mantling of the estuary/interface regions shuts down sand transport seasonally. On a decadal scale, the demise of the Tran De subchannel seems likely because its flows are weak, and its channel depth is shallow. The shallower depth leads to a more vertically mixed water column, and during estuarine conditions promotes further aggregation of organic-rich particles. Rapid settling ensues, and sediment trapping further promotes muddy sediment deposition and mud mantling of any sand beds that exist, as is evident in multibeam surveys. Historical aerial imagery also suggests the Tran De subchannel has been evolving into a less active transport pathway to the coastal ocean (Nowacki et al., 2015). This feedback between reduced flow in a subchannel and subsequent mixing dynamics suggests that, for these types of large deltaic channels, the sequence of bifurcation, enhanced mixing, sediment trapping in the subchannel with lesser flow, and eventual abandonment should be expected. Abandonment of the Tran De subchannel and focusing of freshwater discharge in the Dinh An subchannel would likely result in a more stratified estuary.

However, erosion of substratum and deepening of channels as sea level rise accelerates would compete with the mixing and settling processes. Each distributary will be affected by a different combination of these impacts, resulting in different winners and losers. Although we are uncertain about how the balance will play out, we know that distributaries are becoming less stable, as has happened in the Ba Lai distributary to the north (Tamura et al., 2012), and channel dominance may shift. Hence, the distributary-channel network in the delta, which in general has been stable over thousands of years, is likely to evolve toward a new equilibrium state.

SUMMARY

The collaborative Mekong Tropical Delta Study conducted in the seaward reach of the Mekong tidal river provides some of the most comprehensive data on this portion of the river to date. We gained new insights into the modulation of fluvial source signals in tidal rivers and estuaries, insights that suggest significant impact on sediment signals reaching the coastal ocean. The integrated studies of hydrodynamics, sediment transport and deposition, and channel morphology shed new light on: (1) the impact of tidally variable discharge and bed stress on sediment pathways and total sediment flux, (2) the interaction of mud and sand through depositional processes at the seabed, and (3) the role that mixing plays in particle settling within the tidal river interface and estuary, with feedbacks through channel depth to choking of a bifurcated distributary. In sum, the sediment source signal that leaves the purely fluvial end member of the tidal river is dramatically altered as it transits through the tidal river and estuary, a zone where fluvial process dominance yields to tidal process dominance before the river waters reach the coastal ocean.

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AUTHORS

Andrea S. Ogston (ogston@uw.edu) is Professor, School of Oceanography, University of Washington, Seattle, WA, USA. **Mead A. Allison** is Program Director, The Water Institute of the Gulf, Baton Rouge, LA, USA, and Professor, Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA, USA. **Robin L. McLachlan** is a graduate student in the School of Oceanography, University of Washington, Seattle, WA, USA. **Daniel J. Nowacki** was a graduate student at the School of Oceanography, University of Washington, Seattle, WA, USA, now Research Oceanographer, US Geological Survey, Woods Hole, MA, USA. **J. Drew Stephens** was a graduate student in the Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA, USA, and is now Hydrogeologist, North Carolina Department of Environmental Quality, Raleigh, NC, USA.

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