Sediment Trapping Pathways and Mechanisms through the Mekong Tidal River, Mangrove Shoreline and Subaqueous Delta

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LONG-TERM GOALS

A long-term goal of our sediment transport and deposition investigations is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. The general aim of this project is to investigate how forcing processes affect the sediment-transport dynamics that control the delivery and retention of fine-grained sediment through tidal rivers and in shallow-water coastal regions. We strive to understand how the delicate balance of ebb and flood sediment fluxes is maintained to create tidal flat and mangrove complexes, and distributary shoals and islands within tidal rivers. These environments are characterized by variable bathymetry and seabed stability, and our goal is to evaluate the processes that influence the transport pathways, seabed erosion/deposition, and morphological development in shallow tidally influenced systems.

Sediment is eroded, transported, and trapped via a myriad of processes along the continuum from terrestrial to oceanic environments. At present, we are focusing on sedimentary phenomena in relatively unstudied components within a source-to-sink framework: the connection between the tidal river and the subaqueous delta on the inner continental shelf, and sediment sinks within vegetated/mangrove shoreline complexes. Our overall hypothesis is that sediment-transport signals of flux magnitude, grain size, and dominant pathways are modulated within the tidal river and tidal floodplains en route to the continental shelf, and thus processes in these regions exert a control on the ultimate fate of sediment particles.

OBJECTIVES

This research is designed to investigate sources and sinks of sediment in the tidal river and intertidal areas of the overall source-to-sink system. We report here on results obtained from two seasonal field experiments as part of the Tropical Deltas DRI on the Mekong River delta (Fig. 1). Our objectives focus on the following four areas:

1. **Transport pathways in the tidal river.** In many large rivers the tidal reach is largely unstudied, and the sedimentary dynamics within them control the magnitude and routing of particles onto the continental shelf. We hypothesize that there are mutually exclusive pathways for sediment on flood and ebb tides that control the deposition of sediment into distributary
islands, impact the storage and release of sediment in both the main stem and floodplain areas, and alter the delivery mechanisms to the continental shelf, thereby placing controls on sediment fate.

2. **Sediment retention and release on mangrove/vegetated intertidal areas.** Along the main stem tidal river and coastal banks are shorelines lined with vegetation (mangroves at the

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**Figure 1.** Mekong River delta basemap. Map at top shows Landsat 7 ETM imagery acquired 13 February 2002 with “channel” study sites. Tidal transects occupied during the two seasonal cruises are indicated A-D. Bottom left shows “shelf” instrument sites (black triangles), and middle right inset shows instrumentation plan as part of the collaborative “mangrove” project.
seaward fringe and other brackish-water vegetation in the fresher reaches). We seek to explore the tide and wave-driven forces routing sediment to and from the intertidal mangrove shorelines, and to contrast these processes to those investigated in previous studies of unvegetated intertidal regions (e.g., Tidal Flats DRI).

3. **Sediment dispersal on the subaqueous delta.** Sediment discharged to the shallow subaqueous delta from the Mekong River is actively building a subaqueous clinoform deposit that extends along the Ca Mau peninsula. We propose to investigate the surface and bottom boundary layer transport dynamics that drive linkages between sedimentary signals in the tidal river, subaqueous delta, and mangrove shorelines.

4. **Understanding sedimentary processes on large tropical deltas.** The tidal Mekong River has been highly impacted by humans, and the sub-aerial delta is the site of a large proportion of Vietnamese agricultural production. Our work on the tidal river and shoreline regions of other large tropical deltas, the Fly (past NSF program) and the Amazon (past and ongoing research), allows comparison of features that occur in a largely pristine capacity, with those in the human-impacted Mekong environments.

**APPROACH**

Our general approach is to use in situ observations to evaluate the hydrodynamics, sediment fluxes, and sediment characteristics within the sub-environments listed above. Data from fixed instrumented stations and boat-mounted platforms allow us to investigate each morphological setting. We determine water and sediment fluxes and evaluate the roles of varying meteorological forcing on the sediment-transport dynamics. In addition, we strive to work with other investigators to enhance modeling and remote sensing efforts, and to develop an overall understanding of the system dynamics.

*Transport pathways in the tidal river:* We investigated water and sediment fluxes in the tidal river during preliminary studies and the major collaborative experiments by deploying fixed time-series instrumentation over the fortnightly cycle and surveying transects over complete 24-hour tidal cycles. Preliminary investigations were conducted in the lower tidal river (Song Hau distributary) in August 2012 and April 2013 in the region where the tidal river separates around Cu Lao Dung (Fig. 1); and the measurement campaign was expanded in September 2014 and March 2015 in collaboration with fellow DRI collaborator M. Allison of Tulane University. In these studies, we conducted hydrodynamic and sediment transport studies on transects that encompassed the transition from fluvial tidal river to estuarine. Transects consisted of 24-hour occupations across the channels in order to delineate semi-diurnal variations in fluxes by continuously operating an ADCP to measure current velocities and backscatter (see summary of discharge conditions in Table 1 obtained from these measurements during both preliminary and collaborative studies). We also profiled with CTD/OBS, and collected water and suspended-sediment samples for evaluation of grain size and concentration. In addition we deployed fixed sensors along the tidal river/estuarine continuum that measured water-surface elevation, salinity and suspended-sediment concentration. The integrated data sets provide information on the pathways and fate of fine-grained sediment through the lower reach of the Song Hau distributary of the Mekong River. In order to complete our understanding of the sedimentary dynamics in the tidal river, we are working closely with M. Allison whose group is focused on sand transport and bed morphology to fully understand the processes and resulting morphologies within the tidal main stem of the Song Hau.
Sediment retention and release on mangrove/vegetated intertidal areas: In February 2014, we undertook a “mini-mangrove” experiment to investigate the feasibility of doing experimental work in this mangrove fringe. Subsequently in the September 2014 and February 2015 coordinated DRI experiments, Aquadopp high-resolution current profilers, wave gauges and OBSs were deployed on the bed in collaborative arrays along two cross-shore transects at two ends of the Cu Lao Dung mangrove forest (Fig. 1), and maintained over a fortnight. To explore the connections between sediment flux and bed evolution and structure in the mangroves, time-series data were collected simultaneously in both the SW and NE study sites over a spring-neap cycle during the two dominant seasonal conditions: high river discharge during the NE monsoon, and low river discharge during the SW monsoon. Our focus with these studies is on fluid and sediment exchange between the tidal river channels, the offshore shoal, and the mangrove forest. The data will be used to investigate the mechanisms by which tidal processes serve to import or export sediment over hourly to weekly time scales.

Sediment dispersal on the subaqueous delta: The third environment that links together the coastal system is the subaqueous delta that forms on the inner shelf. To investigate the processes and pathways and whether this region is a source or a sink of sediment relative to the tidal river and mangrove shoreline deposits, we deployed time-series instrument packages over a tidal cycle on the upper and lower foreset and bottomset regions of the active deposit during the NE monsoon and the SW monsoon. We combined those observations with shipboard ADCP and profiling data collected throughout the region. The dataset is limited due to lack of security of the instrumentation. However, there is little known about the active sedimentary processes on the inner shelf and these are some of the first observations of this type made in the region. These data will inform us on the role (and time scales) of the offshore deposits in storing sediment that may ultimately be cycled back into the tidal river or drawn into the mangrove forests under specific environmental conditions.

Understanding sedimentary processes in large tropical delta system: In order to extrapolate our findings in the Mekong system to other large tropical river systems, we plan to synthesize past work done by our research group on other deltas, including the Fly River and the Amazon River. We compare flow dynamics and sedimentary processes. These systems are vast and it is recognized that only specific sections or processes can be addressed in each system. The near-continuous man-made levee structures along the shorelines of the Mekong River create a system without porous boundaries, and therefore we can isolate main stem channel processes better, while in the Amazon River with little human impact, we can address the natural interactions between the channels and tidal floodplains, and how the relationship with the tidal floodplain impacts sedimentary dynamics in the main stem of the river.
WORK COMPLETED

In this year, we conducted the major collaborative experiments that comprise the Tropical Deltas DRI, consisting of field efforts in September 2014 and March 2015. Jointly with C. Nittrouer, UW, we arranged for instrumentation to be shipped and returned, and organized visas, transportation, research vessels, etc., for the DRI group. Much effort on the Tropical Deltas DRI has been in planning and organizing the field efforts that have provided a rich multi-investigator data set in the tidal river, mangrove shorelines, and inner shelf. During our pilot investigations, we developed relationships with Vietnamese colleagues and established a path through their political, cultural, and scientific systems to allow us to undertake the collaborative field effort, and thus laid the groundwork for the larger Tropical Deltas DRI efforts.

During the collaborative field experiments, we deployed instrumentation as described in the Approach section. We successfully collected data in all three sub-environments. In the channels sub-project (Fig. 2), 15 tidal transects along the tidal Song Hau, including over 700 CTD/Turbidity casts, 300 water samples, 140 settling videos, and 33 river bed sediment samples were collected. Our field efforts were integrated with M. Allison, who collected concurrent LISST data, isokinetic samples of suspended sediment and multibeam bathymetry. In the mangroves, we deployed four sensors packages split between the NE and SW regions of the mangrove study area, which provide context for all the other DRI experiments conducted in this time period. On the inner shelf, we completed four successful 10-hr instrument deployments/anchor stations (1 in September 2014; and 3 in March 2015), and acquired several dozen hours of ADCP transect measurements and more than 100 CTD casts.

Analysis and interpretation of the sediment and hydrodynamics data are underway, and some preliminary results are presented below. In addition, we have processed data from the preliminary
cruises to address the evolution from tidal river dynamics to estuarine dynamics as it relates to sediment transport and delivery to the coastal environment (see JGR publication: Nowacki et al., 2015). Between the two major seasonal field efforts a planning workshop was coordinated and conducted in San Francisco, CA, associated with the Fall AGU meeting. Initial data from the September 2014 high-flow experiment was presented, and plans made for the following March 2015 low-flow work.

Following the major DRI experiments, a data exchange workshop was organized in HCMC in September 2015, and our data sets presented and discussed with all collaborators on the Mekong research project. We have shared data with remote sensing and modeling colleagues (Wackerman, MDA; Roelvink, UNESCO; Meselhe, WIG), and as a result of the workshop we are starting to share data and concepts with the broader group. One of our goals in the overall DRI is to provide strong linkages between the sub-environments (channels, mangroves and inner shelf).

We helped to organize the Modeling workshop that followed the data exchange workshop. The students associated with this project attended the workshop, and learned to use DELFT-3D and ICM models. This was a valuable contribution to their education and will allow them to interact with the modeling community in an integrated manner.

RESULTS

Central to this program is the interaction between fluvial and marine processes in the environments that sit on this boundary. Our goal is to link the studies in the three sub-projects, but at present our data processing focuses on understanding what happens within each of the sub-project environments. Once these are better understood, we will integrate across boundaries. Initial interpretations and findings include the following.

Tidal controls on hydrodynamics, suspended-sediment concentration, and sediment flux in the tidal river to estuarine reach

Sediment dynamics within the Song Hau distributary of the Mekong River vary due to fluctuating magnitudes of marine and fluvial forces in this freshwater to estuarine tidal river. Seasonal variations in river discharge and estuarine regime result in export of fine-grained sediment when discharge is high and import when discharge is low. In this large tropical river, fine particles are pre-flocculated in the tidal river, which extends ~200 km upstream of the mouth. The tidal fluctuations in bed stress in the tidal river and periodic presence of a salt wedge and associated estuarine turbidity maximum in the estuary influence movement of salt and fine-grained sediment through the system by inducing variations in bed stress, flocculation, settling, and trapping of sediment within the river channel. Many of these factors are controlled by shifts between two estuarine regimes resulting from to seasonal variations in the ratio of river discharge to tidal influence. Generally, the river exhibits partially mixed estuary conditions during times of low river discharge then shifts to salt-wedge conditions during high discharge. Tidal range effects are superimposed on this pattern with neap tides producing a more vertically stratified water column than spring tides. 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 one sub-channel exhibiting more convergent flow, which enhances flocculation and sediment trapping.

Suspended-sediment import and export: The regime change that takes place in the tidal Mekong River has important implications for suspended-sediment import and export from the estuary. During high
flow, the Song Hau exported sediment to the shelf at a rate of about 1.7 t/s, with Dinh An, the largest of the two distributaries, being responsible for about 60% of the total sediment flux. During low flow the Song Hau imported sediment from offshore at about 0.3 t/s, most of which traveled through the smaller Tran De channel. During high flow, the Dinh An distributary exported sediment to the shelf at a rate of about 1 t/s, and during low flow it imported sediment from offshore at about 0.3 t/s. Applying some simple assumptions about yearly river flow patterns yields an annual Dinh An suspended-sediment discharge of about 9 Mt/y. This suggests that the Dinh An discharges about 10% of the estimated 110 Mt/y exported by the entirety of the Mekong system. 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. During low flow, the imported sediment was transported primarily by the estuarine exchange flow and tidal processes (tidal pumping, resuspension, etc.) and the river term was generally not important.

Sediment pre-flocculation in the tidal river: Settling camera analysis of sediment in suspension shows the fine-grained fraction is pre-flocculated at Can Tho where no salt is ever seen, although the tidal range is ~2 m. Flocs in this region reach a diameter of over 200 microns and are likely bio-aggregated. The amount and size of flocculated particles in the surface water remains relatively constant downstream through the Dinh An channel where salt is present in high concentrations at depth but is not typically well mixed throughout the water column. The flocculated fraction almost doubles in the Tran De channel during low flow likely because salt is more vertically mixed throughout the entire column and, therefore, more readily available as a flocculation agent to surface particles.

Figure 3. Preliminary results from instruments deployed on the NE and SW edge of Cu Lao Dung at the edge of the mangrove forest.
Tidal to seasonal sediment fluxes in the mangroves:

Timeseries of wave, current, CTD, and suspended-sediment data were collected simultaneously in both the SW and NE study sites over a spring-neap cycle during the two dominant seasonal conditions: high river discharge during the NE monsoon, and low river discharge during the SW monsoon. These observations show that conditions in the SW mangrove forest are consistently more energetic than in the NE forest, and that the system as a whole is more energetic during the SW monsoon when winds and waves are more intense. Net sediment import into the SW mangrove forest, and export from the NE forest was observed during both seasonal conditions. Sediment export from the NE mangrove forest results from stronger seaward velocities coupled with elevated SSC during ebb tides. In contrast, landward velocities are higher in the SW study site, and SSC varies less over the tide, yielding sediment import during both seasons (Fig. 3).

Sediment dispersal to the inner-shelf clinoform:

To better understand sediment transfer patterns and hydrodynamic controls, we deployed boundary-layer sensor systems coordinated with collection of seabed cores and seismic stratigraphy offshore of the southernmost Mekong distributary in Sept 2014 and Mar 2015 (high and low river discharge/low and high waves, respectively). The boundary-layer instrument packages deployed at three sites on the clinoform (upper foreset, lower foreset, and bottomset) recorded maximum tidal currents in the boundary layer of ~40 cm/s during both seasons (Fig. 4); thus tidal currents provide sufficient energy to mobilize silt at all depths on this segment of the clinoform. However, tidal currents decrease from...
upper foreset to bottomset, and have different seasonal patterns. Furthermore, additional wave energy during seasonal monsoons creates the capacity to mobilize sand at most (or all) depths on the foreset. The results have allowed us to begin analyzing seasonal variations in sediment transport pathways that may mold the clinoform into its present morphology. Specifically, during high-flow periods, intense sediment delivery and dominantly shore-perpendicular currents likely drive cross-shelf transfer and rapid progradation. During low-flow periods, shoreward- and southwestward-dominant currents may compress the sediment package against the coast, maintaining a shallow topset while elongating the feature southwestward. These results suggest that in shallow seas, clinoform growth is partly linked to seasonal changes in currents driven by seasonal changes in river discharge.

**IMPACT/APPLICATIONS**

Rivers are the largest suppliers of particulate material to the world ocean (Milliman and Meade, 1983), and the pathways that sediment takes in the transition from riverine to marine and the resulting water-surface expression can provide information about the bathymetry, shoreline processes, and ultimate fate of these particles. For the major rivers of the world, the gateways to the open ocean include the freshwater tidal reach, which can extend from the mouth upstream for hundreds of kilometers, and brackish to marine intertidal areas. The hydrodynamic and sedimentary processes in these environments remain poorly understood. Of particular interest are areas that temporarily store and release sediment such as tidal floodplains and the channels that incise them, deltaic distributaries and islands, and vegetated and unvegetated tidal areas. Understanding the processes in these environments, their impacts on mass budgets, and the most appropriate means to model and interpret remotely sensed observations of them requires research that is underway at present. The morphology and seabed properties of these river mouth regions affected by tides are linked to the mechanisms and rates of transport and deposition, and our studies aim to enhance the ability to predict these properties in other unstudied areas. Our studies also provide insight for coastal management that can be transferred to other tidal environments, allowing evaluation of the impacts of humans and invasive species on sediment dynamics.

As part of this program, we are working to advance the capacity of US and Vietnamese students and scientists in the field of coastal and marine geology, and, in particular, estuarine and coastal sedimentary dynamics. All of our field activities had both US and Vietnamese student participation and we are training these students on the principles, operation, and data analysis techniques for the instruments we use. We incorporated training activities and short workshops during our field-work visits to Vietnam, and have helped organize and participated in data exchange and modeling workshops in September 2015 (Fig. 5).

**RELATED PROJECTS**

Our pilot data collection set the scene for the highly successful Tropical Deltas DRI field program. The data collected will be closely knit with other data sets being collected as part of this collaborative DRI program. In the tidal river channels, multibeam seabed bathymetry and data on sand transport was collected simultaneously by M. Allison (TU) to incorporate into our overall understanding of sediment transport mechanics through the distributary channels and resulting morphologies within the tidal main stem. In the mangrove fringe, we deployed our stationary instrument set in a coordinated effort with J. Mullarney (NZ)/S. Henderson (WSU); S. Fagherazzi (BU); and Vo Long Hong Phuoc (VNU). Our instrument set provides the deployment-long overview of spatially variable sedimentary conditions, and we lent instrumentation. On the inner shelf, instrumented deployments and spatial
surveys provide dynamical information on the foreset of the prograding clinoform in a coordinated plan developed with C. Nittrouer (UW), P. Liu and D. DeMaster (NCSU), and T. Nguyen (IMGG). We are sharing our data with other participants in the DRI, and are enhancing the interpretations of remote sensing studies (C. Wackerman, MDA) and numerical modeling efforts (D. Roelvink, UNESCO; E. Meselhe, WIG).

The organization and logistics of accomplishing this field work has been a major effort, and has required all participants (US and Global) to work closely together to design instrument arrays that will obtain the best possible data set with the least amount of overlap. As part of this effort, we continue to assist with the organizational tasks for the DRI, and are working diligently to integrate the Vietnamese scientists into the data collection and analysis, and ultimately their understanding of their major river system.

We have sustained a small parallel program studying tidal river and vegetated shorelines in the Amazon River dispersal system, initially funded by NSF International Programs. The macro- to mesotidal Amazon system provides a contrasting large tropical deltaic environment that has had little anthropogenic modification, while the mesotidal Mekong system has been intensely manipulated by mankind. Comparison of processes across these two study areas allows us to discuss the effects of anthropogenic impacts. We have continued our initial with now-ONR-Global funded collaborators Nils Asp and Pedro Walfir and have hosted visits for students (Susan Rodrigues, UFPA; Estefania Godinho, UFSC) and researchers (Nils Asp, UFPA), and assisted with publications (Asp et al., in revision).
PUBLICATIONS (2014-2015)


Published Abstracts:


Ogston, A.S. etc. Large tropical river mouth sediment-transport dynamics and linkages to coastal sediment transport and deposition. Fall AGU Meeting. 11-15 December 2014. San Francisco, CA.

Nowacki, D.J. etc. Sediment dynamics within the intertidal floodplain of the lower Amazon River. Fall AGU Meeting. 11-15 December 2014. San Francisco, CA.