

## **Processes Controlling Transfer of Fine-Grained Sediment within and Between Channels and Flats on Intertidal Flats**

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### **LONG-TERM GOALS**

A long-term goal of our sediment transport and accumulation investigations is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. The general goal of this project is to investigate how forcing processes (e.g., tidal asymmetry, winds, river discharge and biological activity) affect the sediment-transport dynamics that act to import or export fine-grained sediment in intertidal regions. The resulting product is the formation of mud-flat environments with complex morphology (e.g., multiple scales of tidal channels, differing geotechnical and textural characteristic of flats). We investigate processes that transfer fine-grained sediment in intertidal settings between channels and flats and within channels, and relate them to the temporary and longer-term deposits found in those environments – how is the delicate balance of ebb and flood sediment fluxes maintained to create a relatively stable (or unstable) tidal flat complex. Specifically, we are trying to answer the question: What role do tidal (semidiurnal, fortnightly), riverine and other seasonal (winds/waves, temperature, and biological) processes have on the transfer of sediment between tidal-flat environments, and how is this manifested in terms of channel and flat deposits (temporary and longer-term)?

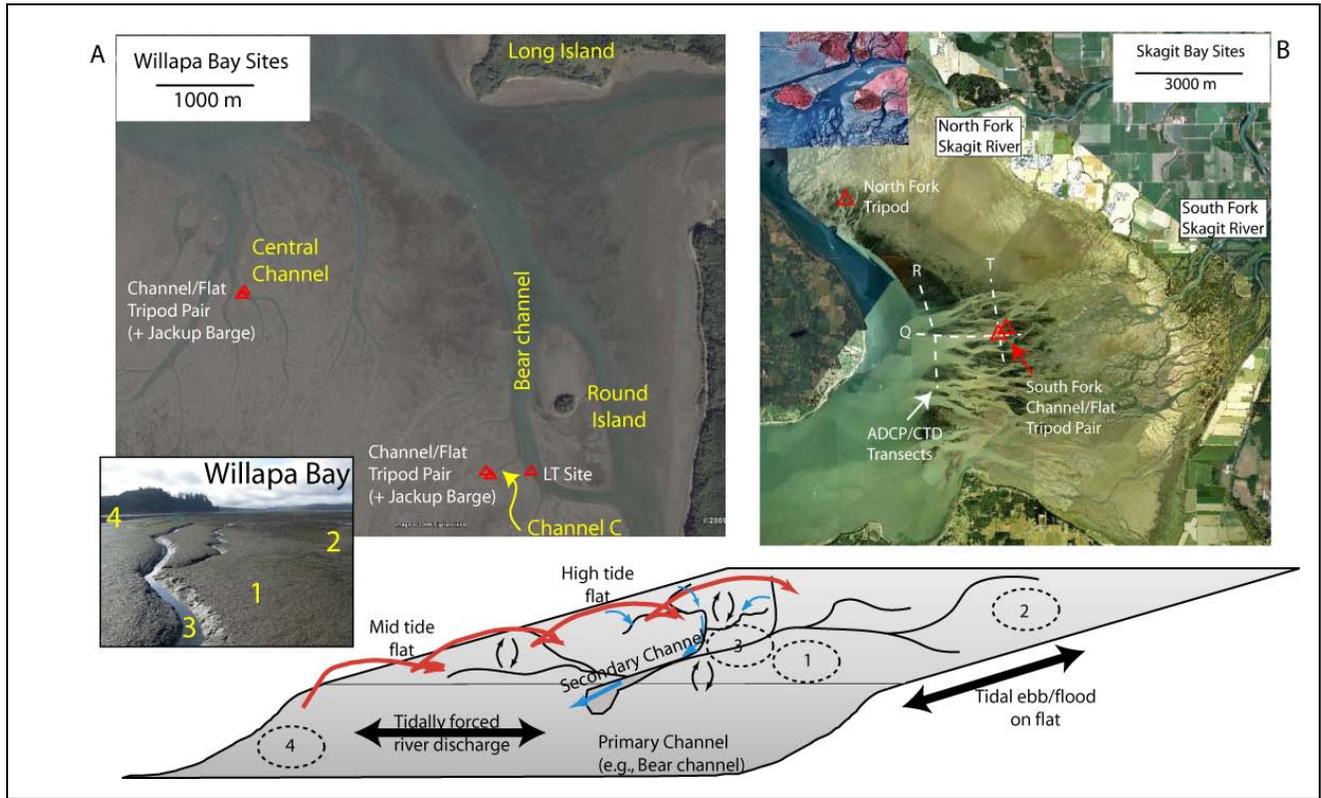
### **OBJECTIVES**

The conceptual model developed from previous work in shallow tidal environments has assumed that tidal asymmetry causes flood-tide currents to generate boundary-layer processes and water-column mixing that act to pump fine sediment onto the flats. Ebb-tide currents deliver sediment from smaller tributary channels to major distributary channels where high-concentration processes either store or episodically transfer sediment from the system – the net sum of these processes varies temporally and spatially over intertidal flats. Our data to date have shown that this model is overly generalized and does not represent the complex physical mechanisms acting on tidal flats. The dominant processes involved in the sediment cycle that control terms in the budget of sediment on tidal flats (Fig. 1) include advected input from rivers, erosion/deposition at the seabed, and transport of sediment in and out of each sub-environment (e.g., primary/secondary channels, flats, etc.). Our studies seek to evaluate these processes over time scales from tidal (semidiurnal, fortnightly, and lunar monthly), to event (e.g., wind storms), seasonal, and potentially interannual time scales to address the following objectives:

1. Evaluate water-column sediment-flux factors and their controls by physical processes (e.g., wind, precipitation, river discharge, and salinity stratification), sedimentological processes (sediment grain size and erodibility) and biological processes (vegetation and benthic biota). Determine how changes in seasonal conditions affect the delicate balance in fluxes and relate changes in transport capacity to temporary sediment storage
2. Relate water-column sediment-flux dynamics to seabed changes in porosity and grain size (resulting from deposition, erosion, bioturbation and dewatering/desiccation) through observation of spatial and temporal seabed elevation variability.
3. Determine the linkages between environments (e.g., import to or export from the flats and between channels and flats) through spatial studies of bed stress, sediment flux and suspended-sediment characteristics that allow a better understanding of sediment dynamics in each morphological setting. Investigate whether sediment fluxes are balanced between channels and flats, and determine the importance of channel order on these sediment dynamics
4. Foster scientific interaction with other participants to investigate the spatial variations in transport processes on the tidal flat. This includes investigators who are focusing on seabed processes, those evaluating relationships between remotely observed signatures and active sediment-transport processes, and those who use models to extract a mechanistic understanding of three-dimensional dispersal of sediment and evolution of seabed characteristics.

## **APPROACH**

The work we have performed under the Tidal Flats DRI has focused on the processes controlling the transfer of fine-grained sediment within and between channels and flats on two contrasting meso-tidal flat environments. The primary study site is in Willapa Bay (Fig. 1a), a muddy embayment in SW Washington that is tidally dominated and receives relatively little direct freshwater influence. This study area allows us to focus on asymmetries in tidal processes. In comparison, the Skagit River tidal flats (NW Washington; Fig. 1b) have similar tidal and wind forcing, but are dominantly composed of sand and have a large river input of freshwater and sediment. The Skagit flats provide study areas with more complex dynamical forcing due to the interaction between tidal and riverine processes; the combination of the Willapa and Skagit sites allows us explore the dynamical differences where tidal asymmetry is impacted by episodic large discharge of freshwater and sediment.



**Figure 1. Location maps for studies in A) Willapa and B) Skagit Bay, and conceptual diagram of characteristic tidal-flat environments. Red arrows indicate shoreward settling/scour lag fluxes, small black arrows indicate resuspension on the tidal flat, blue arrows indicate flux and trapping in the secondary channel environments, and delivery back to a primary channel. The data obtained in this project have shown that these concepts do not represent the processes active on the Willapa tidal flats.**



***Figure 2. Floating acoustic backscatter sensor (ABS) system designed to obtain the suspended-sediment concentration profile during tidal pulses. These pulses occur when water depths on the flat are low (<0.3 m) and traditional instrumentation fails. Additionally, data from a Fiber Optic Backscatter sensor system is shown in Fig. 5 and illustrates the need for sensing systems in extremely shallow water.***

Tidal-flat studies require specialized sensors and platforms designed to capture the processes and products without impact to the soft seabed, particularly in the muddy environment of Willapa Bay. For time-series studies, we have deployed instrument suites on small frames that have minimal impact on the sediment-water interface. We have developed methods that allow mobile access at high to mid tides and create a stationary platform as a jack-up barge, leaving the seabed undisturbed at low tides. Additionally, new sensor systems have been developed that allow us to investigate the brief periods in which much of the sediment flux occurs -- when water depths are very shallow on the flats:

- The jack-up barge has proven to be a valuable tool that increases spatial coverage in tidal-flat studies. It is a unique facility that has enabled the evaluation of velocity and suspended-sediment profiles, sediment size and settling velocity, along with validation through physical samples of the water column and seabed. High-frequency profiling from the jack-up barge allows us to estimate turbulence and shear stresses throughout the water column.
- To capture the tidal pulse in the flux of water and sediment that occurs when the water just exceeds the elevation of the flats, sensor systems have been adapted for this shallow and highly changeable environment (Fig. 2). The first observations of flat skimming flows and the associated profiles of suspended-sediment concentrations have been made using a FOBS (fiber optic backscatter system) with sensors spanning the variable-depth water column (Fig. 3). Data from a system with floating acoustic sensors (ABS) also achieves a similar purpose and is being compared to the FOBS data.

## WORK COMPLETED

Field work at Willapa Bay was initiated in summer 2008, and has continued to the present. A long-term monitoring station was installed on the southern tidal flats of Willapa Bay (Fig. 1), and has been maintained over the two years encompassing focus experiments conducted near this location. The long-term station was dismantled 24 September 2010. Focus experiments were accomplished in March 2009, July 2009, Dec 2009/Jan 2010, and March 2010. During each, sensor suites were deployed in pairs with one package in a channel and one on the flat next to channel. In the most recent experiment, the focus was on capturing the tidal pulse – the time when water depth over the flats is <0.3 m. The focus for all participants has been on a secondary channel (channel C; depth ~1m, Fig. 1), but during the winter 2010 experiment, both the primary (Bear Channel; depth ~4m) and the secondary channel were instrumented. Simultaneous detailed temporal studies were performed from the jack-up barge deployed in various configurations to examine flux into and out of a discrete region. At Skagit Bay, two sites on the outer part of the tidal flats were occupied to study shallow intertidal processes, one off the north fork and one off the south fork (Fig. 1b). Field work was minimal during this annual cycle, and data analysis and integration is on-going.

## RESULTS

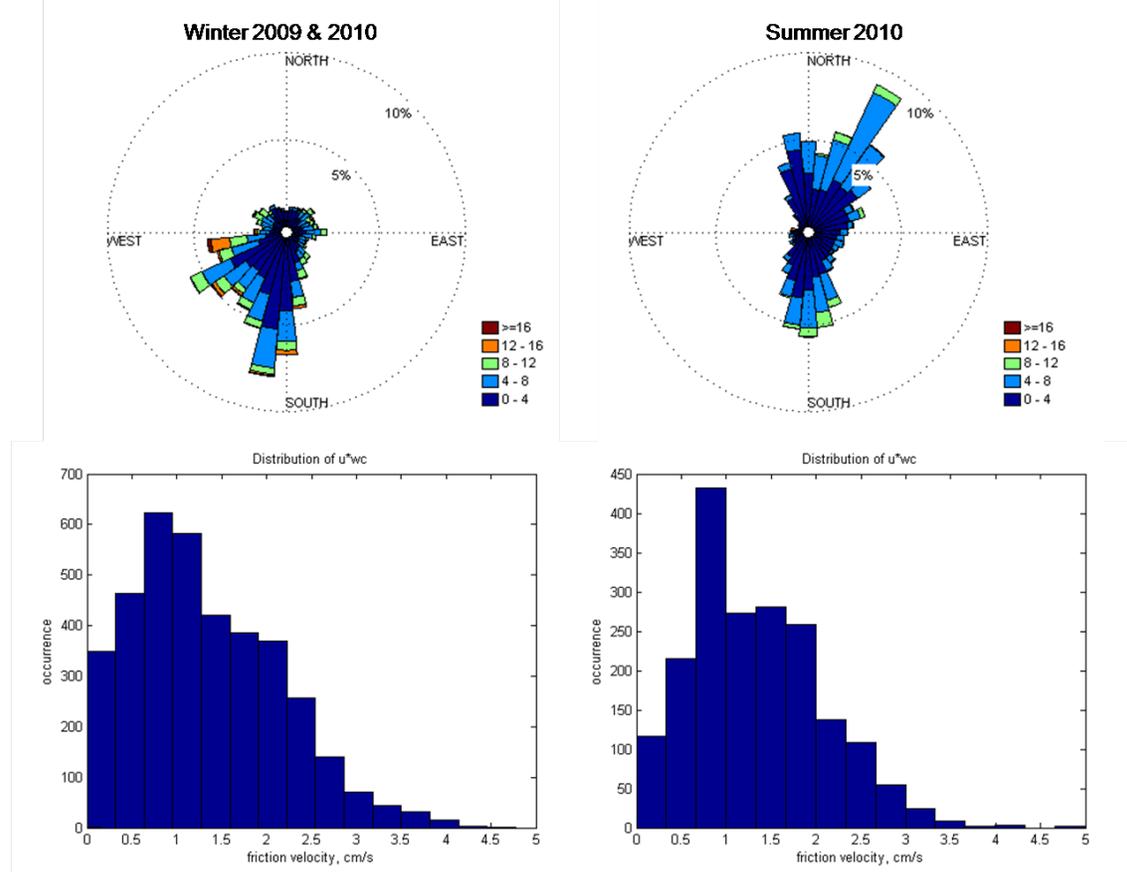
Through studies on these two contrasting tidal-flat systems with similar tidal ranges we are investigating how the magnitudes, timing and characteristics of sediment-transport processes influence the asymmetric tidal circulation and resulting sediment fluxes on tidal flats and result in the ability of tidal flats to import or export fine-grained sediment through different channel morphologies.

### *Willapa Bay Tidal Flats:*

We use data from instrumented tripods in representative channel and flat pairs of different orders to a) better understand seasonal sediment dynamics in variable morphological settings, b) investigate whether sediment fluxes are balanced between channels and flats within different channel morphologies, and c) determine the physical mechanisms responsible for the flux balance.

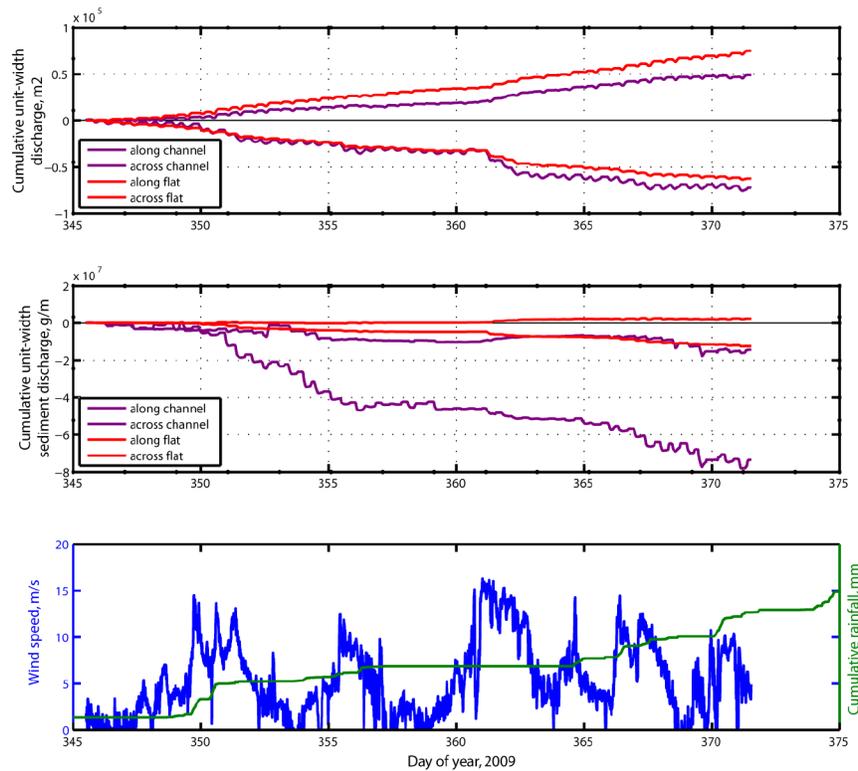
The long-term hydrographic data collected in Willapa Bay between September 2008 and March 2010 reveal the seasonal evolution of how different forcing conditions affect bed shear stresses, the sediment transport capacity of the water column, and the resulting character of the seabed (Fig. 3). A major seasonal change in the hydrodynamic conditions in Willapa Bay was the greater (two orders of magnitude) freshwater input during the winter, which influenced sediment delivery to the system, and increased winter precipitation, which modified the erodibility of sediment on the on the flat surfaces. Averaged seasonally, wind speeds were not drastically different; however greater speeds were reached more frequently during winter. In summer, the reduced riverine input resulted in slightly weaker current velocity magnitudes. The longer fetch over which the summer northerly winds blow enabled greater wave generation during higher tides, increasing wave-orbital velocities. Because current velocities were an order of magnitude greater than wave-orbital velocities, the distributions of combined wave-current shear velocities in winter and summer, were approximately equivalent. In addition, wave-current shear velocities exceeded an estimated critical threshold for resuspension ~50% of the time in each season.

	WINTER		SUMMER	
Naselle River Discharge: Mean & Max	20 m <sup>3</sup> /s	200 m <sup>3</sup> /s	0.85 m <sup>3</sup> /s	5.2 m <sup>3</sup> /s
Salinity: Mean & Range	17	1-21	27	25-30
Wind Speed: Mean & Max	4.9 m/s	17 m/s	3.7 m/s	10 m/s
Current Velocity: Mean & 90 <sup>th</sup> percentile	20 cm/s	40 cm/s	18 cm/s	33 cm/s
Wave-Orbital Velocity: Mean & 90 <sup>th</sup> percentile	2.6 cm/s	4.8 cm/s	3.1 cm/s	5.6 cm/s
$u_{wc}$ : mean & 90 <sup>th</sup> percentile [ $u_{crit}$ : 0.8-1.2 cm/s]	1.3 cm/s	2.4 cm/s	1.4 cm/s	2.3 cm/s
Suspended-Sed. Concentration: Mean & Max	60 mg/L	3200 mg/L	8 mg/L	275 mg/L



**Figure 3. A summary of the typical and extreme forcing conditions, as well as the resultant bed shear velocities and water column properties averaged over the summer (July, August, and September) and winter (November, December, January, and February). Data from both winter 2008/2009 and 2009/2010 are averaged in the winter summaries, and the summer data are from 2009. Wind roses show winter winds originating from the southwest, and summer winds generally from the northeast. Histograms of the combined wave-current shear velocities show little difference between summer and winter conditions.**

Although shear stresses exerted on the seabed did not vary greatly between summer and winter, the concentration of suspended sediment measured in the water column was one to three orders of magnitude greater in the winter. The large volume of suspended sediment during winter temporarily deposited as a drape across the channels, and, via constant tidal forcing, was subsequently transferred onto the flats, where it consolidated and accumulated throughout the summer season. Lower concentrations in summer indicate decreased sediment availability, which was likely due to seasonal conditions such as the development of benthic diatom biofilms on the seabed and increased sun exposure during low tides, both of which increase the erosion threshold of the mudflat and trap particles settling from the water column.

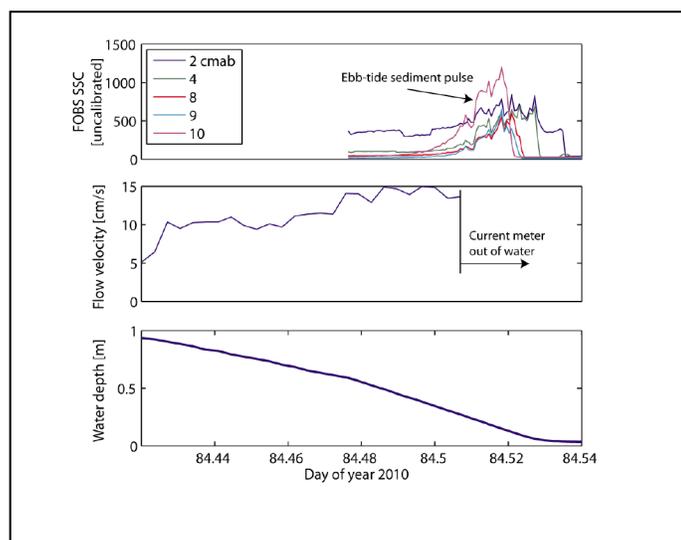


**Figure 4. Cumulative unit-width water and sediment discharge in a secondary channel and adjacent flat over a 27-day deployment in December 2009/January 2010. Residual unit-width discharge is flood oriented (top panel), indicating the presence of a larger-scale circulation in southern Willapa Bay. Residual sediment discharge (middle panel) is similarly flood dominated in both the channel and flat. Wind and rain events (bottom panel) are significant factors in modifying the magnitude of the residual discharge.**

When data are compared between the study sites, channel morphologies were found to influence the asymmetric tidal circulation and resulting sediment fluxes on tidal flats. The flats on the topset of the Skagit River delta are sandy with a network of braided channels, and the muddy flats in Willapa Bay

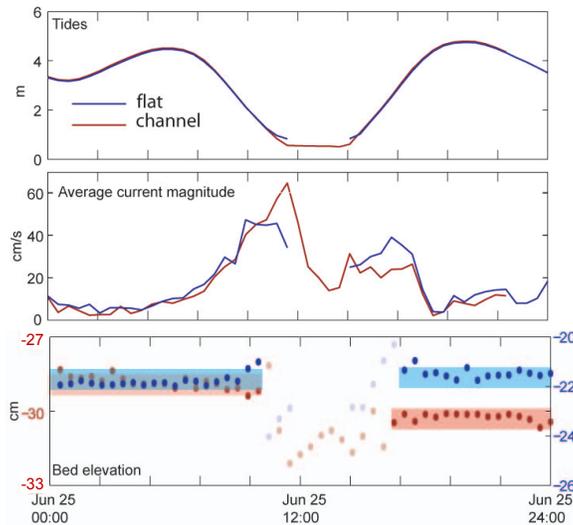
are incised by a dendritic network of steep-sided channels. The Skagit flats efficiently export fine-grained sediment, and the on the Willapa flats, the fine-grained sediment is generally retained.

Within the channels of both systems, currents were observed to be strongest in channels when the water-surface elevation was near to that of the surrounding flats and flow was confined within channels. In contrast to the pulse of high suspended-sediment concentrations observed at mid-tidal elevation in a secondary channel at Willapa Bay, concentrations were highest at low tidal elevations in the channels of Skagit Bay. This indicates that in the Willapa system, there is a more intense transfer of sediment from the flats to the channels and suggests greater temporary storage of sediment on the flat. In the braided Skagit channels, sediment is supplied through channel bed reworking with less transfer between channels and surrounding flats.



**Figure 5. Uncalibrated suspended-sediment concentration, near-bed flow velocity, and water depth at an instrumented tripod on a flat near a secondary channel. Suspended-sediment concentration was measured within 10 cm above the bed (cmab; top panel). As water levels drop, flow velocity increases (middle panel).**

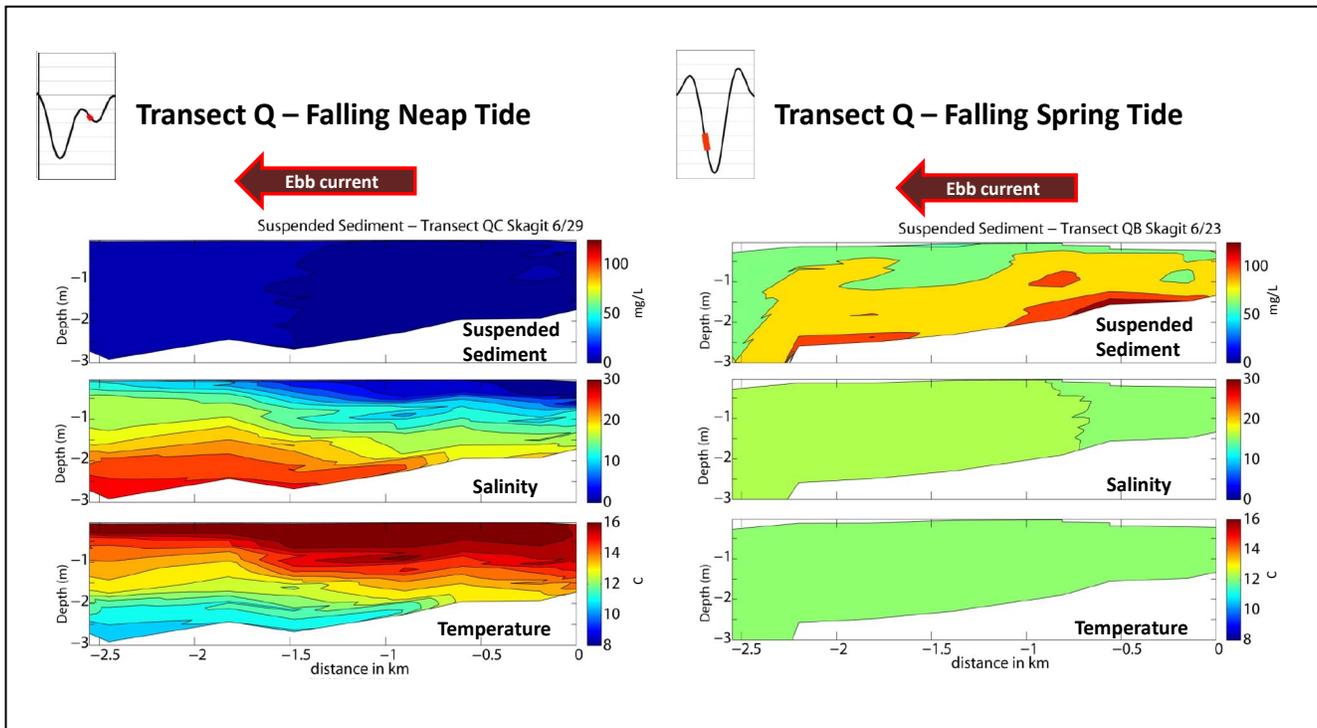
Results from focused experiments in winter 2009-2010 show channels of all orders in southeastern Willapa Bay were flood dominated (Fig. 4). This was driven by longer durations of and sustained high velocities during flooding tides, and suggests that larger circulation patterns were active within the tidal flat complex. The deployment periods were characterized by a range of meteorological conditions, including rain and several wind events. The wind events were correlated with increased flood dominance of water and sediment transport. High-resolution water-column velocity and backscatter profiles reveal complex sediment-flux dynamics between channel and flat environments. Pulses of velocity and SSC were observed in the channel during flooding and ebbing tides when water levels were near the flat elevation, a phenomenon often observed in tidal flats and salt marshes. Instrumentation deployed near the bed on the flat measured elevated SSC when flat water depth dropped below 10 cm (Fig. 5). This “skimming” of sediment on the flat contributed to the SSC pulse in the channel during ebbing tides. Water convergence from the flat led to increased channel bottom stresses and resuspension of freshly deposited sediment temporarily stored within the channel. These fine-scale observations allow us to address the mechanisms that govern the total sediment balance of channels and flats within tidal flat systems.



**Figure 6. Channel and flat water-surface elevation, current magnitude, and bed elevation. There is an approximately 2 cm reworking of the channel seabed when the tide is low and flow is channelized. The flat seabed remains relatively untouched during the period (pale symbols represent data where the sensor is not trustworthy due to shallow or no water).**

*Skagit River Tidal Flats:*

Our studies show that in contrast to Willapa Bay, strong river discharge and tidal currents within the braided tidal-channel system act to deliver, rework and rapidly export sand and mud to the seaward edge of the flat. Hydrodynamic measurements were paired with seabed sampling, and they provide the link between episodic to seasonal transport dynamics and seabed deposits. At high discharge, the braided-channel system delivers limited fine-grained sediment to the flat. For example, during a winter flood event, suspended-sediment concentrations were large in channels, where 5 cm of deposition formed as river discharge began to wane. Strong tidal currents produced shear stresses capable of resuspending sand-sized particles. The stresses acted to rework the channel seabed (Fig. 6), whereby particles are resuspended and fine-grained particles can then be exported to the flat edge. Evidence of this reworking is seen by 1-2 cm of deposition and erosion within single tidal cycles.



**Figure 7. During a falling, neap tide, there is low amounts of sediment in suspension and a well stratified water column. Neap tides have limited ability to bring sediment to flat edge. During a falling, spring tide, the water column is mixed and sediment is released from inner flat storage to the outer edge of the flat.**

The fate of the estuarine particles in suspension is dictated by tidal currents over the flats. Spring flood tides trap fluvial particles in the water column of the upper flat, where observed SSC reached 100 mg/L and was <10 mg/L on the outer flat. On the ebb tide, particles were released and carried to the flat edge and SSC was >50 mg/L across the entire flat (Fig. 7). The water-column and seabed data show that tides and river discharge within the braided-channel system deliver particles to the flat and then act to export sediment off the flat.

## IMPACT/APPLICATIONS

To understand the source-to-sink sediment transfer from rivers to marine deposition, we must develop our understanding of the gateway between the land and ocean -- shallow-water regions spanning the tidally influenced river to the inner shelf. Tidal flats are one type of environment found in this shallow-water realm. The settling lag/scour lag concept has been generally invoked to understand the retention of sediment and development of intertidal flats. Our data show that this process is not the controlling process on all intertidal flats, and require that we rethink our concepts of transport and deposition of fine-grained sediment over the range of tidal-flat morphologies. Seabed properties of tidal flats are linked to the mechanisms and rates of transport and deposition on the flats, and our studies aim to enhance the ability to predict these properties in other areas. Our studies also provide insight for coastal management that can be transferred to other tidal-flat environments, allowing evaluation of the impacts of humans and invasive species on sediment dynamics. Both of the sites

being studied have areas actively being restored, and we have consulted with teams undertaking these efforts.

## **RELATED PROJECTS**

The Tidal Flats DRI projects are tightly knit. This work will provide interactions with all participants through field efforts, meetings, shared results and scientific discussions. This study is providing valuable collaborations with other research groups working under the Tidal Flats DRI, particularly by providing dynamic measurements in to compare with models. Understanding the transport regime is integral to understanding the properties of the seabed. Our data provide validation for modeling and laboratory studies concerning transport on tidal flats. The two-year-long monitoring package allows the group to monitor and observe during less-frequent events, gives context to the seasonal focus experiments and will aid the interpretation of imagery that has been obtained. Focus experiments in Willapa Bay have been coordinated among a group of investigators. Data has been, and will continue to be shared as groups continue their integration and synthesis work. In addition to collaborations within the Tidal Flats DRI, the two small instrumented tripods were deployed on the outer Skagit tidal flats in a study coordinated with an NSF project (Dr. C. Simenstad, UW) investigating ecosystem dynamics, and the size of ecotones for different species of benthic organisms.

## **PUBLICATIONS (2009-2010)**

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### *Abstracts*

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Boldt, K., Nittrouer, C., Ogston, A. (2009) Linking sediment transport processes to laminated seabed deposits in a fine-grained tidal flat: Willapa Bay, WA. Coastal and Estuarine Research Federation 20<sup>th</sup> Biennial Conference, Portland OR, 1-5 November 2009.

Hsu, T.-J., Chen, S.-N., Ogston, A.S., (2010) A numerical investigation of fine sediment transport at intertidal flat. AGU Meeting, San Francisco, CA. 13 Dec 2010.

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Lee, K.M., Ogston, A.S., Nittrouer, C.A. (2010) Episodic and Seasonal Export and Retention of Fluvial Sediment on the Skagit River Tidal Flats, Washington State. Ocean Sciences Meeting, Portland, OR. 24 Feb 2010.

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