SUSPENDED-SEDIMENT TRANSPORT THROUGH A LARGE FLUVIAL-TIDAL CHANNEL NETWORK

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INTRODUCTION

The Sacramento – San Joaquin River Delta (the Delta) is formed at the confluence of the Sacramento River and San Joaquin River, the two main watersheds draining California's Central Valley (Figure 1). Once an extensive tidal marsh system, the Delta has been subject to an array of changes since the discovery of gold and subsequent development of California in the mid-1800s. These changes include the following: construction of channel levees and draining of tidal marshes for agriculture; hardening (rip-rap) of existing channels and construction of new channels/canals to support water conveyance; hydraulic gold mining activities which introduced large quantities of fine sediment to the Delta in the late 1800s; construction of large dams in the watershed in the mid-1900s that trap sediment and reduce sediment loads to the Delta; construction and ongoing dredging to maintain shipping channels through the Sacramento River (upstream to Sacramento) and San Joaquin River (upstream to Stockton); and the construction of large pumping facilities in the south Delta that export water to the San Joaquin valley and southern California for agricultural and urban uses. These physical modifications have affected the hydrodynamics and sediment transport characteristics of the Delta (Lund et al., 2007, Whipple et al., 2012), which have in turn affected the aquatic ecosystem. In addition to the physical modifications, the ecosystem has been affected by direct biological modifications, in particular the introduction of non-native species.

Delta smelt, a fish species endemic to the Delta currently listed as Threatened under the Federal Endangered Species Act and Endangered under the California Endangered Species Act, is currently a major regulatory, management and scientific focus in the Delta. The Delta smelt, along with other native and non-native species, experienced abrupt population declines in the early 2000s, referred to locally as the Pelagic Organism Decline., or POD. While the POD is generally thought to be the result of multiple stressors, Delta smelt habitat and migration patterns have been linked with turbidity and temporal changes in turbidity such as "first flush" river runoff events (for a review of Delta smelt habitat studies refer to Sommer and Mejia, 2013). First flush refers to the first major runoff event in the watershed that produces substantial sediment loads and increases in turbidity in the Delta. Increases in turbidity in the southern Delta in the vicinity of the State Water Project and Central Valley Project pumping facilities (near Clifton Court Forebay, see Figure 1) have been linked to high entrainment of Delta smelt at the facilities (Grimaldo et al., 2009), which can lead to severe curtailments of water deliveries south of the

Delta on which 25 million people depend for at least part of their drinking water supply. Because turbidity in the Delta is caused by suspended sediments, studies of sediment transport dynamics are important for understanding Delta smelt habitat and informing Delta smelt management decisions.

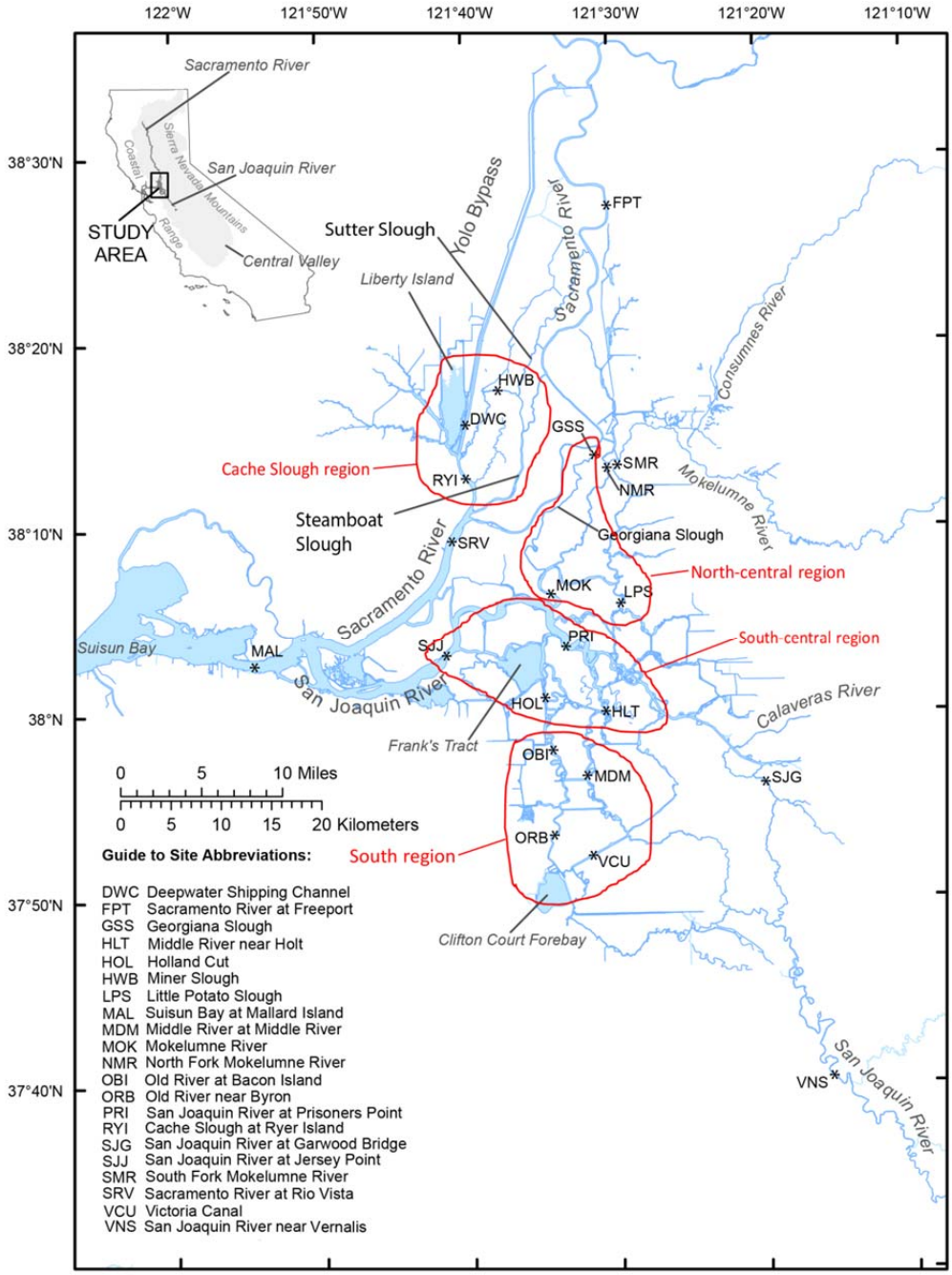

Figure 1 – Site map showing locations of gages and region outlines used in this study.

The objective of this paper is to describe the advection and dispersion of a first flush sediment pulse through the Delta. We focus on a single event that occurred in December 2012 (Figure 2, first pulse beginning around 1-Dec-2012) to illustrate these processes, because this event provided a very clean signal from the Sacramento River and throughout the Delta due to relatively low sediment flux from the San Joaquin and Mokelumne rivers (Figure 2). The Sacramento River is the dominant source of water and sediment to the Delta (Wright and Schoellhamer, 2005), such that events like the December 2012 first flush can be considered fairly typically in terms of influencing Delta turbidity. In addition, these first flush events are known to be a cue for Delta smelt migration upstream into the Delta (Sommer et al., 2011, Bennett and Burau, 2014) and potentially into the zone of influence of the south Delta export facilities, where they are subsequently salvaged at the export facility fish screens and ultimately resulting in export curtailments.

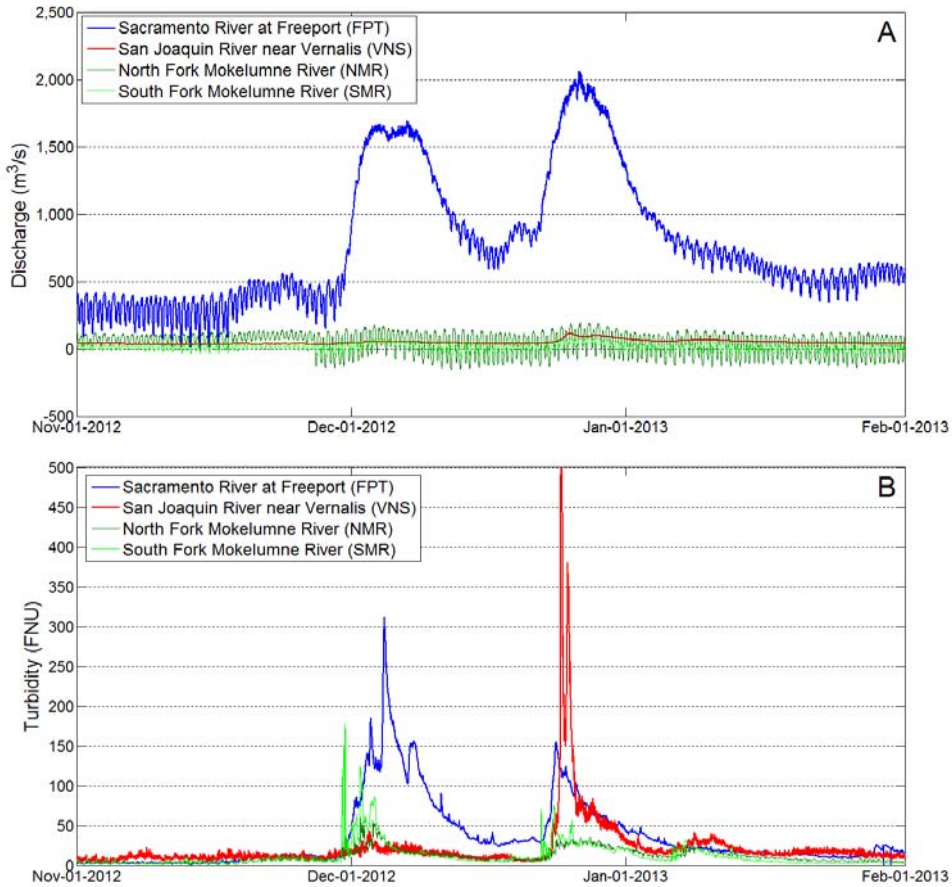

Figure 2 – Discharge (A) and turbidity (B) at upstream Delta boundaries.

METHODS

The U.S. Geological Survey (USGS), California Department of Water Resources (DWR), and Bureau of Reclamation (BoR) maintain an extensive flow and water quality monitoring network

in the Delta. Flow monitoring (USGS) is conducted using index velocity methods (Ruhl and Simpson, 2005, Levesque and Oberg, 2012). *In situ* continuous monitoring of turbidity, temperature, and conductivity (USGS, DWR, and BoR) is accomplished using multi-parameter sondes (Wagner et al., 2006). Suspended-sediment concentration (SSC) time series are generated through calibration of turbidity sensors (Rasmussen et al., 2009). In the analysis presented herein, we rely directly on the turbidity data (instead of SSC) because 1) turbidity is monitored at more sites than suspended sediment, and 2) the basic results of the analysis are the same whether turbidity or suspended sediment are used (we do not present sediment flux or sediment budgets). Figure 1 shows the gaging stations that were used in this study. Flow and velocity data were accessed from the USGS NWISweb database (http://waterdata.usgs.gov/ca/nwis/); turbidity data were accessed from NWISweb (for USGS data) and the California Data Exchange Center database (http://cdec.water.ca.gov/index.html) (for DWR and BoR data). The discharge at Mallard Island (downstream boundary of the Delta) and the discharge from the south Delta pumping facilities (daily water project exports from the vicinity of Clifton Court Forebay, Figure 1) were obtained from the DAYFLOW program (http://www.water.ca.gov/dayflow/).

Several metrics were computed from the time series data and used to evaluate transport processes during the event: 1) the pre-flood (base) and peak turbidity at each site; 2) the travel time of the turbidity peak to each gage from the upstream boundary (Sacramento River at Freeport); 3) the duration of the rising limb in turbidity at each site; and 4) the distance to each gage (along the most direct channel route) from the upstream boundary. These metrics were used to evaluate the transport pathways of the sediment pulse as well as the mechanisms controlling transport between sites.

RESULTS AND DISCUSSION

Time series of turbidity (panel A), tidally-averaged discharge (instantaneous discharge averaged over a tidal period, approximately 25 hours, panel B), and velocity (panel C) for all sites are shown in Figures 3-7. Each figure presents the conditions in a different region of the Delta, in the downstream direction from the source of the sediment pulse (the Sacramento River): Figure 3 shows conditions along the mainstem Sacramento River; Figure 4 shows conditions in the Cache Slough area; Figure 5 shows conditions in the north-central Delta; Figure 6 shows conditions in the south-central Delta; and Figure 7 shows conditions in the south Delta region. In each figure, the legend is organized from upstream to downstream. The conditions at the upstream boundary (Sacramento at Freeport) are shown in all figures; the y-axis scales are the same for Figures 3-5 but are condensed in Figures 6-7 (south-central and south Delta) in order to illustrate the dispersion of the sediment pulse as it moves southerly through the Delta. Refer to Figure 1 for the locations of the gaging stations identified in the time series figures.

The evolution of the sediment pulse as it travels down the mainstem Sacramento River (Figure 3) illustrates the processes of advection and tidal dispersion. At the upstream boundary (Freeport), flows are typically unidirectional (with some tidal influence) under low Sacramento River inflows (e.g. most of the year), but during the runoff event the tidal influence was washed out and the signal was entirely fluvial (Figure 3C). Further downstream at Rio Vista, the turbidity peak was reduced and the tidal signal is evident. At Mallard Island (downstream boundary of the Delta), the turbidity peak was further reduced and the signal was substantially broadened (increased time to peak). These features are the basic elements seen throughout the Delta as the sediment pulse moves through the fluvial-tidal transition.

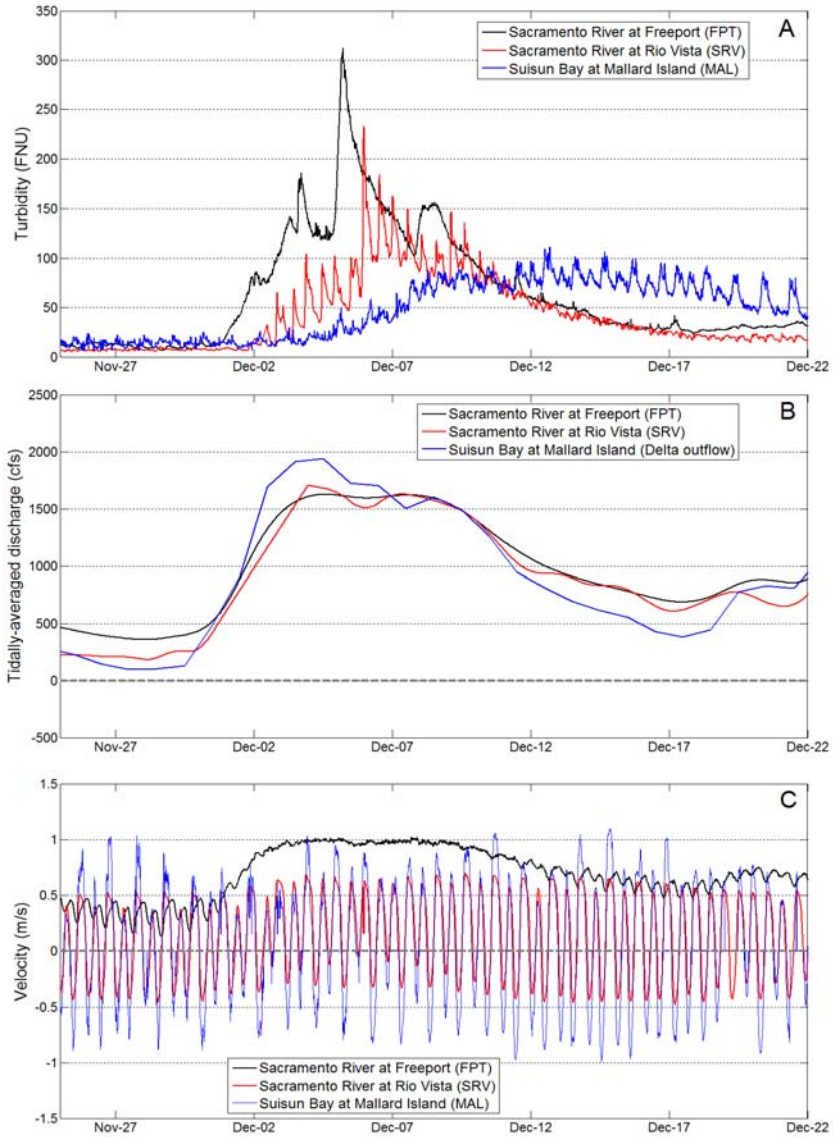

Figure 3 – Turbidity (A), tidally-averaged discharge (B), and velocity (C) along the mainstem Sacramento River.

Conditions in the Cache Slough and north-central Delta regions are shown in Figures 4 and 5, respectively, and illustrate the influence of the Sacramento River distributary channels. As the Sacramento River encounters tidal influence (around Freeport), it splits into several distributary channels (in downstream order: Sutter Slough, Steamboat Slough, Georgiana Slough, see Figure 1). During low flow, each of these distributary channels typically carries 10-20% of the upstream Sacramento River flow; during high flow, a combination of Sutter and Steamboat Sloughs can carry about 40% of the flow upstream at Freeport.

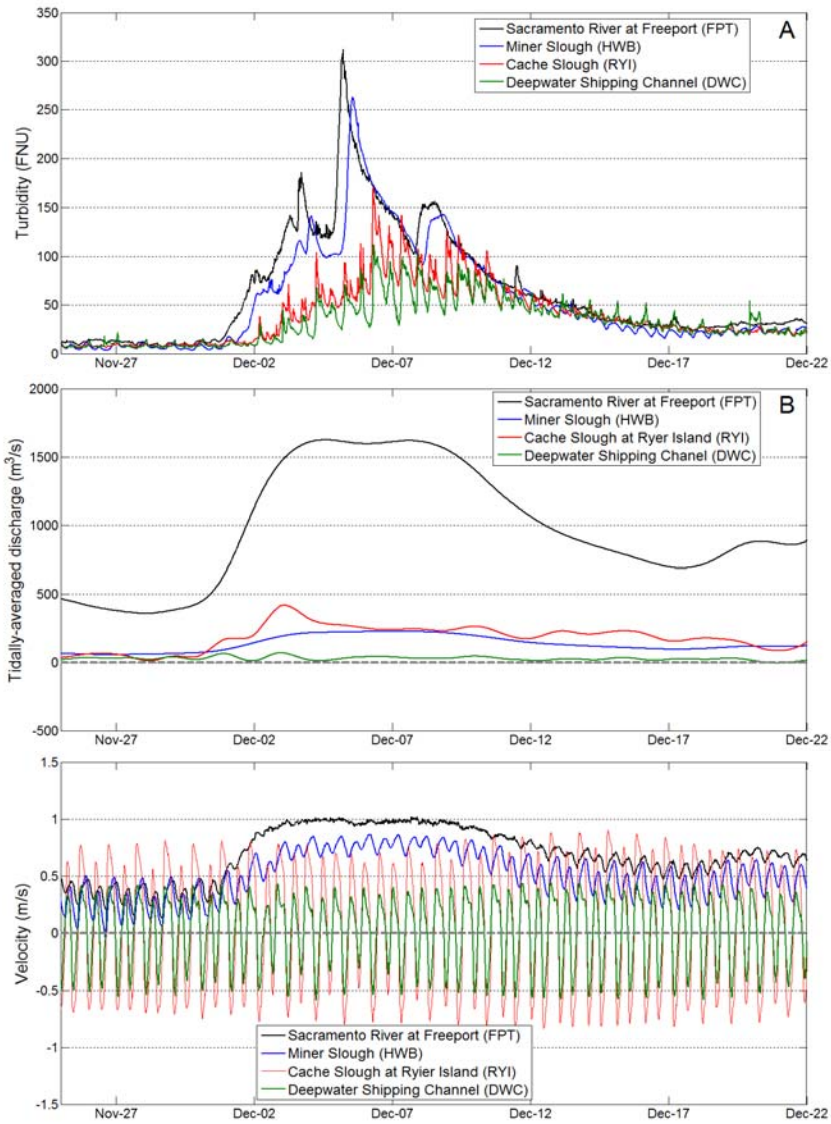

Figure 4 – Turbidity (A), tidally-averaged discharge (B), and velocity (C) in the Cache Slough region of the Delta.

Figure 4 shows that, based on the sampling stations we analyzed, Miner Slough is the primary pathway for sediment to reach the Cache Slough area; the turbidity signal in Miner Slough is nearly identical to that on the Sacramento at Freeport and the sites further downstream in the

Cache Slough area illustrate the effects of tidal dispersion and deposition (reduced turbidity peaks, increased tidal variability). Similarly, Figure 5 shows that Georgiana Slough is the pathway for sediment to reach the north-central Delta (the Delta Cross Channel is closed during high flow events); the turbidity signal in Georgiana is nearly identical to the Sacramento River at Freeport and the sites further downstream (Mokelumne River, Little Potato Slough) demonstrate the effects of tidal dispersion and deposition. This pathway also has particular importance for transport to the south Delta, as discussed below.

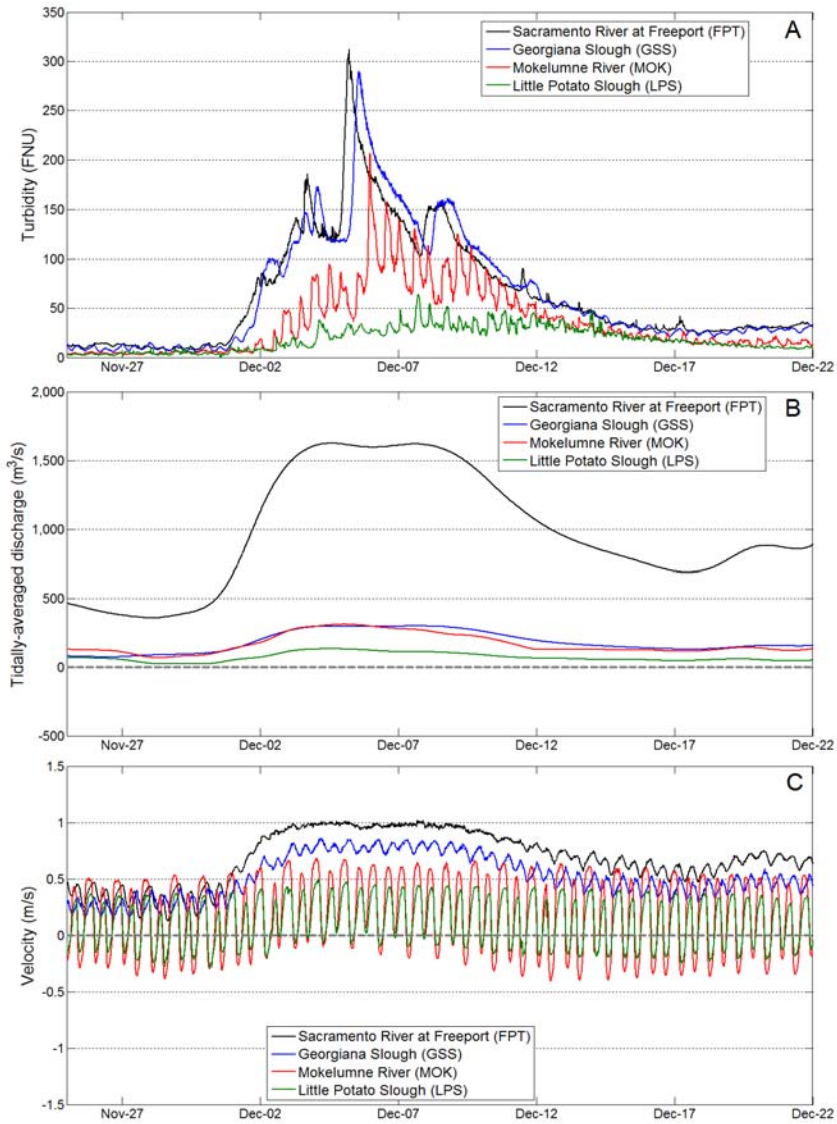

Figure 5 – Turbidity (A), tidally-averaged discharge (B), and velocity (C) in the north-central region of the Delta.

Conditions in the south-central Delta and south Delta regions are shown in Figures 6 and 7, respectively. The y-scale in the turbidity panels was reduced in order to better illustrate the signals, but the signal at Freeport was included for illustrative purposes. The sites in the south-

central Delta (Figure 6) include several along the San Joaquin River and have turbidity signals similar to other downstream tidal sites (such as Mallard Island), with reduced turbidity peaks and broader distributions. The sites in the south Delta (Figure 7) have even lower turbidity peaks and broader distributions due to tidal dispersion and deposition. An important aspect of transport processes in these regions is the direction of the tidally-averaged (net) flows (panel B) and the influence of the water export facilities. Negative net flows in these regions indicate "reverse" (landward) flows to the south toward the export facilities. In the absence of water exports, the net flows in these regions would be seaward and the mechanism for sediment transport into the south Delta (advection with the landward net flow) would not exist. Thus, the water export facilities play a key role in elevating turbidity in the south Delta during Sacramento River runoff events.

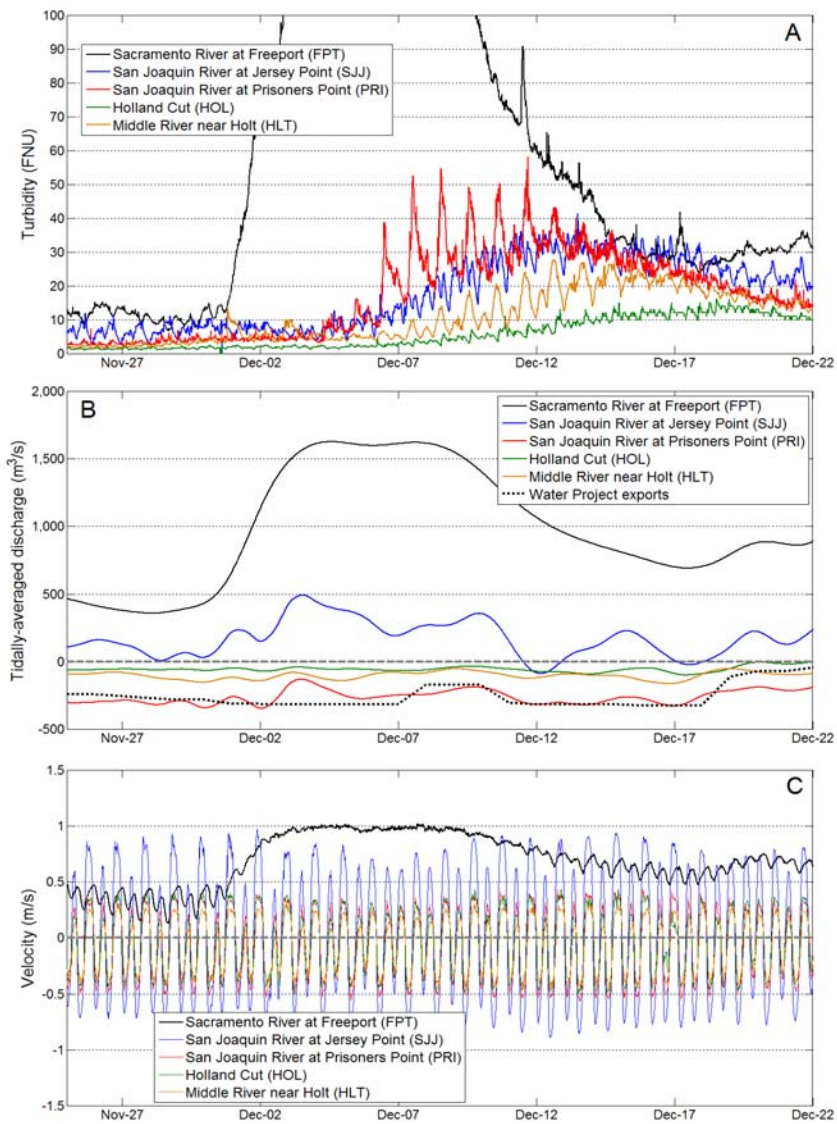

Figure 6 – Turbidity (A), tidally-averaged discharge (B), and velocity (C) in the south-central region of the Delta.

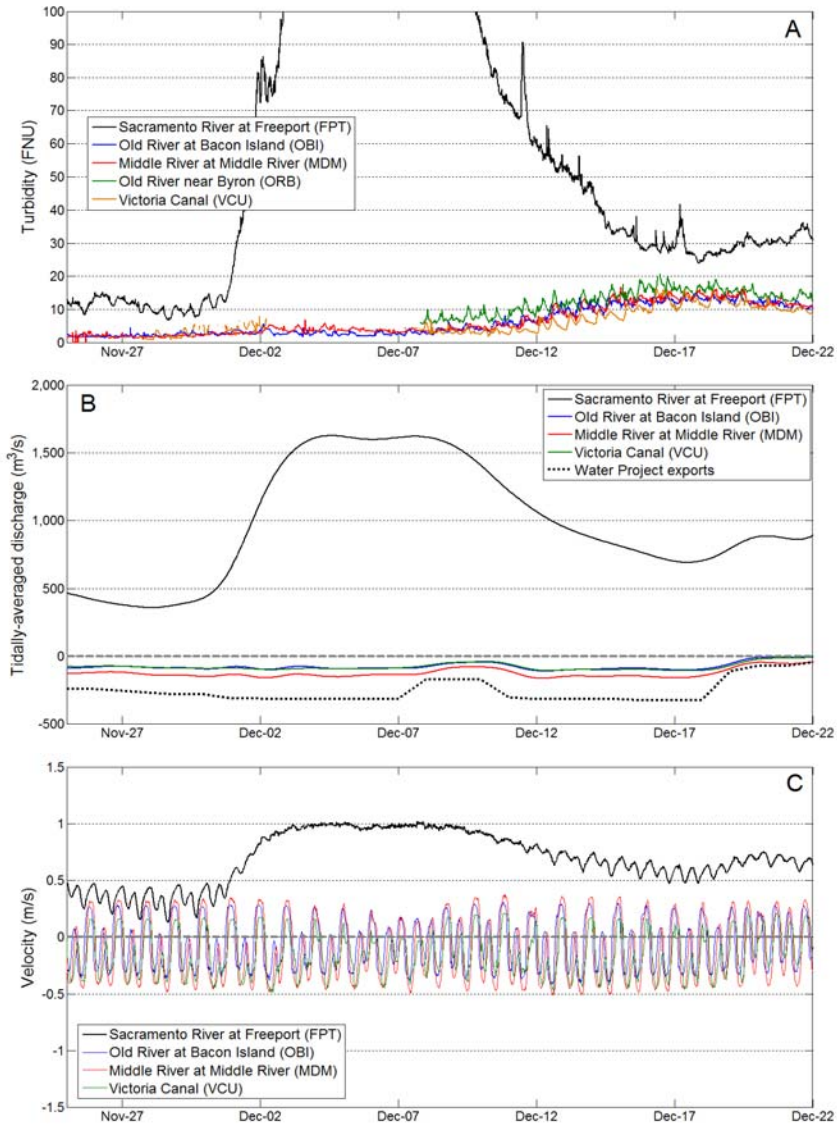

Figure 7 – Turbidity (A), tidally-averaged discharge (B), and velocity (C) in the south region of the Delta.

Figure 8 summarizes the pre-flood and peak turbidities for all of the sites, organized by region and in a downstream direction within each region. The decreases in peak turbidity in the downstream direction illustrate the processes of tidal dispersion and deposition that occurs through the fluvial-tidal transition. Figure 8 also shows the order of magnitude decrease in peak turbidity that occurs from the upstream boundary to the furthest downstream sites (south Delta).

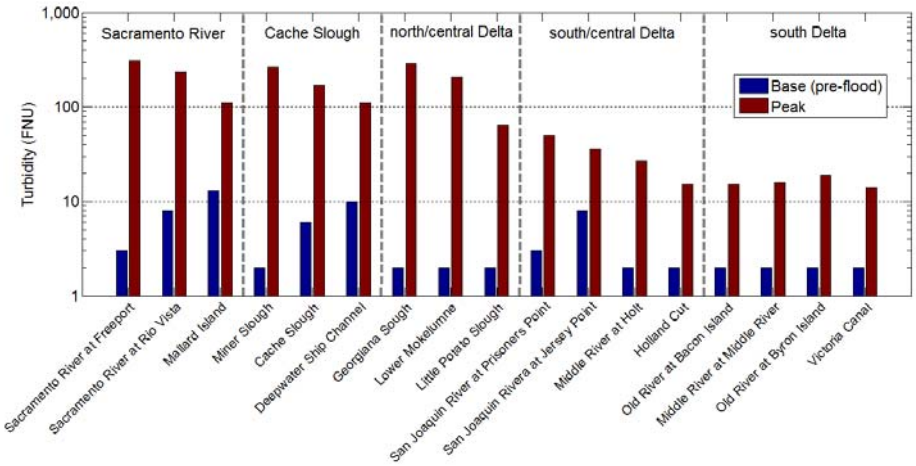

Figure 8 – Pre-flood (base) and peak turbidity at the sites identified in figure 1.

The change in several metrics of the sediment pulse as it moves through the Delta and the fluvial-tidal transition is shown in Figure 9. Three metrics were used: the peak turbidity (panel A); the travel time of the turbidity peak (measured from the Sacramento River at Freeport, panel B); and the duration of the rising limb of the turbidity signal (panel C). These metrics are indicative of the advection and dispersion processes between a given site and the source of the sediment pulse, and are plotted in Figure 9 as a function of distance downstream from the Sacramento River at Freeport. For all metrics, a relatively abrupt transition is apparent at 50-60 km downstream from Freeport. This is roughly the distance along the north Delta distributary channels to Cache Slough, as well as the distance along the Georgiana/Mokelumne pathway to the San Joaquin River. At these locations, there is an abrupt increase in the channel capacity and therefore an increase in tidal forcing and concomitant reduction in the net flow velocity. Thus, sites upstream of these junctions illustrate primarily fluvial responses with a weaker tidal influence, and sites downstream illustrate reduced fluvial influence with much greater tidal influence. Figure 9B demonstrates an order of magnitude reduction in the velocity of the sediment pulse through this transition, from about 0.6 m/s in the fluvial region to about 0.04 m/s in the tidal region. This is accompanied by about a two-fold increase in the duration of the rising limb of the pulse (Figure 9C), from about 4 days in the fluvial region to about 8-10 days in the tidal region. Finally, elevated pre-flood (base) turbidities at Mallard Island, Rio Vista and the Deepwater Ship Channel are given as one of the reasons Delta smelt are found at these location under pre-first-flush conditions (Sommer and Mejia, 2013).

SUMMARY OF MAIN FINDINGS

Herein we have examined the evolution of a sediment pulse, originating from the Sacramento River, as it moved through the fluvial-tidal transition in the Sacramento-San Joaquin Delta. This examination revealed the following main findings related to transport processes:

- Sacramento River distributary channels convey sediment to different regions of the Delta, resulting in elevated turbidity in these regions. In particular, Georgiana Slough is the primary pathway for sediment from the Sacramento River to the south Delta region.
- Sediment transport in the northern region of the Delta, near the upstream source, is dominated by fluvial processes. Tidal influence increases dramatically at about 50-60 km from the Sacramento River at Freeport, where the north Delta distributary channels encounter Cache Slough and the Mokelumne River system encounters the San Joaquin River
- Water export facilities in the south Delta result in negative (landward) net flows in this region and contribute to the landward transport of sediment and elevated turbidity in the south Delta.

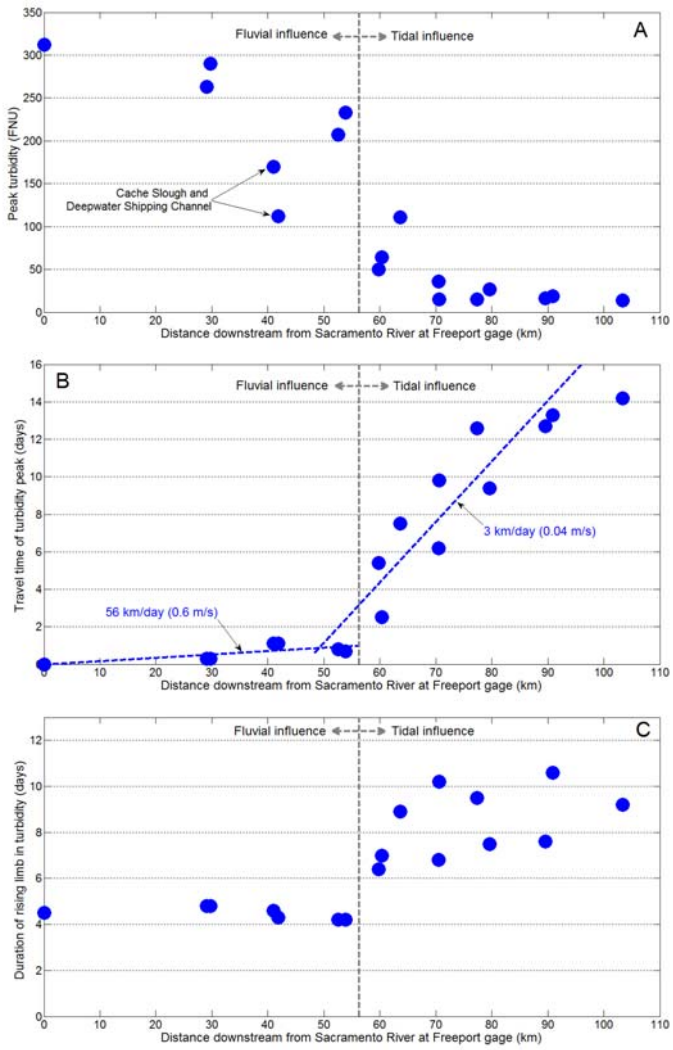

Figure 9 – Peak turbidity (A), travel time of turbidity peak (B), and duration of the rising limb in turbidity (C) versus distance downstream from the upstream sediment pulse source.

REFERENCES

Grimaldo, L. F., Sommer, T., Van Ark, N., Jones, G., Holland, E., Moyle, P. B., and Smith, P. (2009). Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: can fish losses be managed?. North American Journal of Fisheries Management, 29(5), 1253-1270.

Levesque, V.A., and Oberg, K.A., 2012, Computing discharge using the index velocity method: U.S. Geological Survey Techniques and Methods 3–A23, 148 p., http://pubs.usgs.gov/tm/3a23/

Rasmussen, P.P., Gray, J.R., Glysson, G.D., and Ziegler, A.C., 2009, Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. C4, 52 p.

Ruhl, C.A., and Simpson, M.R., 2005, Computation of discharge using the index-velocity method in tidally affected areas: U.S. Geological Survey Scientific Investigations Report 2005-5004, 31 p.

Sommer T, Mejia F, Nobriga M, Feyrer F, Grimaldo L. 2011. The Spawning Migration of Delta Smelt in the Upper San Francisco Estuary. San Francisco Estuary and Watershed Science (2011) 9 (2), 16 pages.

Sommer, T., and Mejia, F., 2013, A Place to Call Home: A Synthesis of Delta Smelt Habitatin the Upper San Francisco Estuary, San Francisco Estuary and Watershed Science 11(2), 27 p.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, 51 p. + 8 attachments; accessed April 10, 2006, at http://pubs.water.usgs.gov/tm1d3

Whipple, A., Grossinger, R., Rankin, D., Standford, B. & Askevold, R. (2012) Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process. San Francisco Estuary Institute.

Wright, S. A., and D. H. Schoellhamer, 2005, Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento–San Joaquin River Delta, Water Resour. Res., 41, W09428, doi:10.1029/2004WR003753.