INTRODUCTION

The Sacramento-San Joaquin Delta is the largest delta on the west coast of the United States. It is formed where the confluence of California’s two largest rivers (the Sacramento and San Joaquin) meet the ocean tides and has a significant physical gradient from fluvial to tidal. It is a semi-diurnal system (two high and two low tides per day). Today, the Delta is one of the most manipulated in the United States. Once composed of many shallow, meandering and braided dendritic channels and dead-end sloughs and wetlands, it is now a network of leveed canals moving clear water around subsided islands. It historically has supported a biologically diverse tidal wetland complex, of which only 3% remains today (Whipple et al., 2012). It has also witnessed a collapse in the native fish populations. The Delta provides critical habitat for native species, however the hydrology and water quality are complicated by manipulations and diversions to satisfy multiple statewide objectives. Today water managers face co-equal goals of water supply to Californians and maintenance of ecosystem health and function. The Delta is a hub for both a multi-hundred-million dollar agricultural industry and a massive north-to-south water delivery system, supplying the primary source of freshwater to Central Valley farmers and drinking water for two-thirds of California’s population. Large pump facilities support the water demand and draw water from the Delta, further altering circulation patterns and redirecting the net flow toward the export facilities (Monsen et al., 2007).

Fluvial sedimentation, along with organic accumulation, creates and sustains the Delta landscape. Hydraulic mining for gold in the watershed during the late 1800s delivered an especially large sediment pulse to the Delta. More recently, from 1955 to the present, a significant sediment decline has been observed that is thought to have been caused mostly by the construction of water storage reservoirs that trap the upstream sediment supply (Wright and Schoellhamer, 2004). Today, one concern is whether the volume of sediment supplied from the upper watershed is sufficient to support ecological function and sustain the Delta landscape and ecosystem in the face of climate change, sea level rise, and proposed restoration associated with the Bay Delta Conservation Plan (http://baydeltaconservatationplan.com). Ecosystem health is a management focus and 150,000 acres of restoration is currently proposed, therefore it is of increasingly important to understand the quantity of sediment available for marsh and wetland restoration throughout the Bay Delta Estuary. It is also important to understand the pathways for sediment transport and the sediment budget into each of three Delta regions (figure 1) to guide restoration planning, modeling, and management.

In this paper, we present our preliminary findings while revisiting previous sediment flux research (Wright and Schoellhamer, 2005). Our current understanding of the hydrology of the Delta has been improved by a larger network of monitoring sites and new, higher quality
instrumentation to monitor turbidity, which we use as a surrogate for suspended sediment. The central Delta, specifically, is an extremely complicated and dynamic mixing zone hydrologically influenced by changes with river discharge, tides, seasons, diversions, and flow path modifications. Sacramento River flow into the central Delta is reduced by gates on the Delta Cross Channel (DCC figure 1) that are periodically closed, directing flows to the west Delta and San Francisco Bay. One critical issue is the migration of native fish through the Delta and the physical entrainment with the current into the south Delta. This often leads to mortality at the California and Federal pumping facilities and compromises population resilience (Kimmerer, 2008; Grimaldo et al., 2009). The annual spawning migration of delta smelt from Suisun Bay and the western Delta into the central and south Delta where they can potentially be entrained is believed to be triggered by the increase of Delta turbidity. The increased turbidity is caused by the influx of suspended sediment from the Sacramento River into the central Delta during the first major storm of the year (also known as the “first flush”).

Our objectives for this paper are to 1) quantify annual sediment budgets for the Delta during water years 2011, 2012, and 2013, 2) to describe the primary pathways for sediment into each Delta region shown in figure 1, and 3) to explain the timing and magnitude of sources of sediment into the Delta. We evaluated the primary sediment peak of winter storms with a focus on the significance of the Georgiana Slough pathway (from GEO to MOK on figure 1) into the central Delta channels. One specific question we wanted to address is how much sediment moves into the central Delta during the peaks of the storm-related-sediment pulses during the initial prespawning migration of delta smelt compared to the total annual sediment load for a given water year (figure 2). The sediment information has been a missing link to migration and entrainment analysis. We know that the first significant rise in turbidity in winter, initiated by a big storm, is thought to initiate migration (Bennet et al., 2014; Grimaldo et al., 2009) and the majority of salvage (i.e. captured and “saved” from entrainment) occurs during net negative flows (Kimmerer, 2009; Grimaldo et al., 2009). We hope, therefore, to help managers understand the effects of sediment and turbidity on fish migration in terms of the quantity and pathway of sediment that is transported to the pump facilities because salvage often leads to mortality.

**METHODS**

Turbidity, a surrogate measurement for calculating suspended-sediment concentrations (SSC) and load, is a water quality parameter that describes the cloudiness or opacity of the water due to suspended solids (Gray and Gartner, 2008). Turbidity as a surrogate has been successfully used for sediment analysis and demonstrated by Rasmussen and others (2005), Urich and Bragg (2003), Lietz and Debiak (2005), Wood and Teasdale (2013), Buchanan and Morgan (2010). Turbidity data from our network of sites described in figure 1 were corrected for calibration drift and fouling errors as described in Wagner et al. (2006).

Discharge data came from the California Department of Water Resources (DWR) and U.S. Geological Survey (USGS). Channel discharge was calculated from measurements using acoustic Doppler current profiler (ADCP) data and the index velocity method for tidal channels (Ruhl and Simpson, 2005). These data were accessed through the Water Information System (NWIS) [http://waterdata.usgs.gov/ca/nwis](http://waterdata.usgs.gov/ca/nwis), with exception to Mallard Island discharge data.
which came from the DWR DAYFLOW website and was accessed from http://www.water.ca.gov/dayflow.

Figure 1. The north, central, and south regions of the Delta suspended-sediment-monitoring network are demarcated by the red dashed lines. We show 17 sediment-flux-monitoring stations, eight stations where sediment fluxes were estimated, and three boundary stations (FPT, YOLO, and VNS) which measure the primary sediment inputs from the Sacramento and San Joaquin Rivers. Measurements of tidal flow using acoustic Doppler current profilers were available at all stations so that fluxes could be estimated. The Georgiana Slough pathway is the channel between GEO and MOK.

The in-stream optical turbidity sensors and water samples were used to monitor suspended-sediment concentrations at seventeen sites (figure 1) strategically chosen from the larger network to allow for regional estimates of sediment loads and deposition. Suspended-sediment concentration data were collected across a number of Delta sites by the USGS during water years
2011-2013 (October 1, 2010–September 30, 2013). At all sites discussed herein, turbidity data was collected from optical sensors that are co-located with ADCPs to measure flow. Discharge weighted suspended-sediment concentrations (SSC$_{xs}$) were derived from depth-integrated water samples collected across the cross-section using the equal discharge increment technique and standard samplers (Edwards and Glysson, 1999). The output of the optical turbidity sensors were calibrated to the cross-sectional-average SSC so that a record of SSC, suspended-sediment flux (SSF), and loads could be computed. Yolo Bypass carries flow and sediment from the Sacramento River during floods and sediment loads were estimated using the methods in Wright and Schoellhamer (2005). Total sediment loads entering the Delta were determined by summing loads from the YOLO, FPT, UCS, NMR, SMR, and VNS stations (see figure 1). Sediment loads at Mallard Island were estimated using the approach discussed in McKee et al. (2013). The sediment entering the Delta, but not transported out at MAL, is considered to have been deposited in the Delta.

Figure 2. FTP and GEO turbidity time series, with the time periods isolated out for analysis in each of 2011 (top), 2012 (middle), and 2013 (bottom). These time periods isolated in red are thought to be the critical times associated with the initial migration of prespawning delta smelt. The red dashed line depicts the turbidity threshold of 25 FNU at FPT that was used to depict the storm pulse. Events identified as yielding the first flush span 22 days in 2011, 12 days in 2012, and 26 days in 2013. Note the differing y-axis for each graph.

RESULTS

DELTA SEDIMENT BUDGET AND DEPOSITION ZONES
The Sacramento River and San Joaquin Rivers are dominated by fluvial advection of sediment into the Delta, however the Sacramento River is the dominant source of flow and sediment (Wright and Schoellhamer, 2005). In general, the distributary channels throughout the Delta are also dominated by seaward advection, however, tidal dispersion and sediment settling also occurs. The average deposition/sediment budget for each of the three regions (north, central, and south) during the three-year time period discussed herein, is shown in figure 3 (left panel). The total sediment load into each Delta region for each year is shown in figure 3 (right panel). The largest sediment load to the Delta is from the north and decreases southward. On average,
roughly two-thirds of sediment supplied to the Delta is deposited, (Wright and Schoellhamer, 2005) however the proportion of sediment deposited varies from year to year as is to be expected. For 2011, around 69% of the total sediment load was deposited. In 2012, 45% of the total sediment was deposited, and in 2013, roughly 32% of the sediment was deposited.

Figure 3. Map showing the Delta regions (left) defined by the black dashed line for north, central, and south Delta, and shows the average mass of deposition with the standard error. The bar graph (right) shows the annual sediment load in thousand metric tons to each region for each of 2011, 2012, and 2013. The sediment load from Rio Vista is considered part of the Central Delta. Bold arrows represent the primary paths for the Sacramento and San Joaquin Rivers. Additional pathways within the Delta are represented by red arrows. Note the opposing arrows for Old and Middle Rivers as sediment flux changes seasonally and with flow conditions.

PRIMARY PATHWAYS OF SEDIMENT
The primary pathways for fluvial sediment entering the Delta and it’s regions, are shown in figure 3 (left panel) and figure 4 with bold arrows. The Sacramento and San Joaquin Rivers are the primary pathways of sediment from the watersheds to the north and south Delta respectively, however the maximum annual sediment flux was from the Sacramento River (1085 Kt at FPT in 2011) as shown in figure 4A, during an above average flow year. It carried three times as much sediment into the Delta than the San Joaquin River. In 2013 (a below average flow year), the volume of sediment supplied by the Sacramento River to the Delta was seven times that of the San Joaquin (roughly 80% of the total load into the Delta). Most of the sediment within the main-stem Sacramento River remains in suspension and is transported past Rio Vista and then seaward towards Suisun Bay. A portion of the sediment in the Sacramento River is also advected into various distributaries such as Miner Slough, Streamboat Slough, and Georgiana Slough (figure 4).
Figure 4. Primary pathways of sediment transport for 2011 (A), 2012 (B), and 2013 (C). The major riverine sediment pathways have red polygon arrows and the smaller distributary pathways are shown with red line arrows. The Sacramento River is represented by a black line and the San Joaquin River is represented by an aqua blue line. The east side Consumnes and Mokelumne River pathway to Little Potato Slough is represented by a blue-dashed line. Miner and Steamboat Slough distributaries are in gray, and Georgiana Slough is shown in purple. The sediment loads in thousand metric tons for various sites are shown with red circles proportionally sized.

The sediment from the Sacramento River is advected into distributaries and further transported either into the north Delta/Cache Slough region (north of LCS in figure 1 and figure 4) via 1) Sutter Slough (not shown) to Miner, or 2) Steamboat Slough, or 3) into the central Delta via Georgiana Slough (figures 1 and 4). Georgiana Slough and the Mokelumne River are influenced by the fluvial characteristics of the Sacramento River and sediment in these channels is advected to the central Delta. Most of the suspended sediment observed at site MOK (70% on average) comes from the Sacramento River via Georgiana Slough during the wet season and not directly from the tributaries of the Mokelumne. The Georgiana Slough pathway supplied a larger volume of sediment to the central Delta than the San Joaquin River during both 2012 and 2013 (figure 4B and 4C). In 2013, the annual sediment flux into the central Delta from the San Joaquin River at SJG, was 15% of the flux at MOK. Sediment originating from the Sacramento River can then make its way into the south Delta. In 2012, specifically, the sediment flux seaward from the central Delta was nearly equivalent to the sediment flux advected southward down Old and Middle Rivers (figure 4B).

**DISCUSSION**

**DEPOSITIONAL PATTERNS**

Proportional to sediment supply, on average, the north Delta had the least amount of deposition (30% on average) and the south Delta had the most (figures 3 and 4). This is because of the difference in the magnitude of flow in the Sacramento River compared to the San Joaquin River. Sacramento River sediment transport is dominated by advective processes; sediment remains in
suspension and is carried seaward past Rio Vista (SRV) to Suisun Bay (MAL). In contrast, a large portion of sediment advected down the San Joaquin River settles out of suspension and is deposited in the south Delta region especially during below average flows such as those occurring during 2012 and 2013. Based on a three year average, roughly 70% of the sediment advected down the San Joaquin River past Vernalis (VNS) is deposited in the south Delta Region.

The central Delta had approximately 50% deposition (and the most of any region) in 2011, but had little deposition in both 2012 and 2013. In these two years, the central Delta had the least sediment deposition of all three regions (23%). The Sacramento River alone supplied nearly 85% of sediment to the Delta proper and can account for roughly 70% of the sediment into the central Delta. Furthermore, our data suggest that for 2012 and 2013 (below average flows with little flow and sediment coming from the San Joaquin River watershed), a portion of the sediment entering the central Delta which is not advected seaward, moves further into the south Delta.

South Delta sediment is supplied from the north and the south direction and there is significant deposition. In 2011, when there was above average flow, sediment transport was predominantly seaward down the San Joaquin River. However, in 2012, 82% of the sediment load from the San Joaquin River observed at Vernalis (VNS) stayed in the south Delta. In addition, during 2012 and 2013, the quantity of deposition in the south Delta was greater than the mass of sediment advected down the San Joaquin River past VNS. Sediment is additionally advected into the south Delta from the central Delta because of the net negative flow that the large water pumps facilitate (figure 5). The sediment flux is in the landward direction into the south Delta via Old and Middle Rivers.

CENTRAL DELTA SEDIMENT
In this section, we address sediment transport pathways in the context of delta smelt migration. Specifically, we wanted to know the sediment transport pathways that lead to pumping curtailments either through increased turbidities in the south Delta or smelt salvage at the export facilities. To do this, we computed the sediment load from the first flush storm for each year of 2011, 2012, and 2013 to 1) determine the major contributions to the sediment load and thus increased turbidity in the central Delta and 2) to determine the sediment load of a first flush storm compared to the annual sediment load, to address the potential for making the Delta clearer in the summer if the first flush loads were reduced. Figure 2 shows the time periods which were isolated to compare the first flush sediment loads vs. the annual loads. Though these may not be the largest sediment loads of the year, the turbidity from a first flush event is correlated to fish migration (Sommer et al., 2011) and fish entrainment (Grimaldo et al., 2007) so we consider the first flush turbidity peaks to be the most critical time periods for delta smelt migration (Sommer et al., 2011, Bennett and Burau, 2014). We used a turbidity threshold of 25 FNU to define the first flush peaks at FPT (figure 2).

Sediment from Georgiana Slough is advected to the Mokelumne River and to the San Joaquin River. During low flow conditions, it is the main source of sediment to the central Delta. Compared to the total annual sediment load, the quantity of sediment which moves down Georgiana Slough during the first flush events shown in figures 2 and 6 varies from year to year and depends on flow conditions. In 2011, 21% of the annual sediment load down Georgiana
occurred within 22 days between December 8 and January 4, and 28% of the annual load occurred during the period of December 7 to January 9 (figure 6). Another 48% of the annual load was transported during mid-March to mid-April when approximately 50% of the total annual deposition into the central Delta occurred (figure 7 period 4). In 2012, only 12% of the

Figure 5. The highlighted gray areas in December and July-September represent more negative flow at ORS in 2012 (A) with increased pumping volumes (B), and a steeper negative advective sediment flux slope (C). Positive is ebb flow to the north and seaward; negative is towards the south Delta. Note that the daily pumping volume shown is for the combination of both State and Federal facilities.

Figure 6. Georgiana Slough cumulative sediment load in thousand metric tons (Kt) for 2011, 2012, and 2013 showing the first flush sediment flux for the time periods outlined by the red lines here and coinciding with figure 2.
annual sediment load in Georgiana moved downstream towards MOK during the first flush compared to 2013, when 67% of the annual sediment load was advected downstream during the first flush time period. The largest first flush sediment load from the Sacramento River to the Delta occurred during 2013. Figure 8 shows the sediment supplied to the central Delta by each channel during the 2013 first flush. Eliminating this sediment supply to the Delta would significantly affect the quantity available for subsequent tidal and wind-wave resuspension. Sediment resuspension elevates turbidity and enhances habitat quality.

Figure 7. Approximate proportion of sediment deposition during 2011 within the central Delta from 6 different time periods. The blue line represents the tidally filtered FPT hydrograph image superimposed (unscaled) on the graph to show the flow patterns compared to the deposition patterns.

Figure 8. Total estimated sediment loads in thousand metric tons to the central Delta from each channel during 2013 for the time periods described in figure 2. Sizes of circles are intended to represent magnitude of sediment load and arrows represent direction of transport. The Georgiana Slough pathway to the Mokelumne is shown in red underneath the black arrow. The North and South Mokelumne tributaries are represented by one total (seven thousand metric tons).
CONCLUSIONS

The average sediment load during 2011-2013 to each of three Delta regions decreased from north to south. The north Delta has the largest sediment load, but proportionally, the smallest percentage of deposition because the Sacramento River is dominated by advective seaward sediment transport. Sediment supplied by the Sacramento River is additionally advected down various distributaries such as Sutter Slough, Miner Slough, Steamboat Slough, and Georgiana Slough.

Sediment from Georgiana Slough and the Delta Cross Channel is advected towards the Mokelumne River and into the central Delta; a major contribution to the total sediment supply into the central Delta is from the Georgiana Slough pathway. Sediment from Georgiana Slough is advected into the Mokelumne River and, during the 2013 first flush as described in figure 2, was nearly 70% of the load to the central Delta (south of the MOK and east of JPT). Less than 10% of the total sediment supply to this area was from the San Joaquin River during 2013. The 2013 annual sediment supply to the central Delta was dominated by one month of flow from the Sacramento River. If this supply was eliminated during the winter time period via upstream diversions along the Sacramento River, as proposed by the Bay Delta Conservation Plan, or some other means, the sediment supply to the central Delta in the 2013 example would be reduced by 70%.

Net flow (and advective sediment flux ) is directed from the central Delta to the south Delta toward the export facilities and has been referred to by others as a hydrodynamic “pull” (Arthur et al. 1996, Monsen et al. 2007, Grimaldo et al. 2007). During low flow conditions both tidal dispersion and the effect of the pump facilities limit seaward transport where there is a predominantly net negative advective sediment flux from the south/central Delta into the south Delta.

REFERENCES


