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Recent Advances in Understanding Flow Dynamics and Transport of Water-Quality Constituents in the Sacramento–San Joaquin River Delta

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ABSTRACT

This paper, part of the collection of research comprising the State of Bay–Delta Science 2016, describes advances during the past decade in understanding flow dynamics and how water-quality constituents move within California's Sacramento–San Joaquin River Delta (Delta). Water-quality constituents include salinity, heat, oxygen, nutrients, contaminants, organic particles, and inorganic particles. These constituents are affected by water diversions and other human manipulations of flow, and they greatly affect the quantity and quality of benthic, pelagic, and intertidal habitat in the Delta. The Pacific Ocean, the Central Valley watershed, human intervention, the atmosphere, and internal biogeochemical processes are all drivers of flow and transport in the Delta. These drivers provide a conceptual framework for presenting recent findings. The tremendous expansion of acoustic and optical instruments deployed in the Delta over the past decade has greatly improved our understanding of how tidal variability affects flow and transport. Sediment is increasingly viewed as a diminishing resource needed to sustain pelagic habitat and tidal marsh, especially as sea level rises. Connections among the watershed, Delta, and San Francisco Bay that have been quantified recently highlight that a landscape view of this system is needed, rather than consideration of each region in isolation. We discuss interactions of multiple drivers and information gaps.

KEY WORDS

Hydrodynamics, transport, water quality, Sacramento–San Joaquin River Delta, ocean, watershed, anthropogenic, fluvial forcing

INTRODUCTION

Movement of water and constituents carried by water within the Sacramento–San Joaquin River Delta (Delta) depend on forcing from the Pacific Ocean, the Central Valley watershed, human intervention, the atmosphere, and internal biogeochemical processes. Semidiurnal and diurnal tides from the ocean slosh water back and forth several kilometers daily through the Delta's complex network of channels. The ocean is a source of salinity, the spatial distribution of which can affect flow dynamics and transport. At a longer time-scale, oceanic sea level determines sea level rise (SLR) in the Delta. The Central Valley watershed provides freshwater via river flow episodically during California's wet season, and total runoff varies dramatically inter-annually. The watershed is a source of constituents carried by water including nutrients, contaminants, sediment, and organic particles. Water diversions and associated manipulations of inflow and flow paths alter flow dynamics and transport. Wind can alter Delta water levels and generate wind–waves, which can lift material resting on the bottom into the water column. Biogeochemical processes create sources and sinks of constituents within the Delta. Water and its constituents that exit the Delta in the seaward direction affect San Francisco Bay (the bay).

Technological advances in instrumentation in the past 2 to 3 decades have enabled rapid and continuous measurements of water flow and constituent concentrations. Mike Simpson and Rick Oltmann of the U.S. Geological Survey (USGS) were the first to use acoustic current meters to measure water flow in the Delta, doing so from moving boats (Simpson and Oltmann 1993) and continuously from a fixed station (Oltmann 1995; Ruhl and Simpson 2005). Today, an extensive flow station network in the Delta utilizes acoustic instrumentation (Burau et al. 2016). Optical sensors invented in the 1980s were first deployed in the Delta in the late 1990s to continuously measure suspended-sediment concentration (Wright and Schoellhamer 2005). Optical sensors that continuously measure carbon and nutrients were first deployed in the Delta in the 2000s (Bergamaschi et al. 2012; Downing et al. 2009; Pellerin et al. 2013). When these instruments are deployed with sufficient density to enable several channels or locations to be observed simultaneously, continuous data streams that include all tidal fluctuations can be collected, and these data have led to improved understanding of flow and constituent transport in the Delta.

This paper, part of the State of Bay–Delta Science 2016, summarizes advances in the last 10 years in flow dynamics and how water-quality constituents move within the Delta. Water-quality constituents include salinity, heat, oxygen, nutrients, contaminants, organic particles, and inorganic particles (i.e., sediment). These constituents are affected by water diversions and other human manipulations of flow, and these constituents themselves greatly affect the quantity and quality of benthic, pelagic, and inter-tidal habitat in the Delta. The geographic scope of this paper is the Delta, how the watershed affects the Delta, and how the Delta interacts with the bay and ocean. Though we attempt to cover the breadth of our topic by using a conceptual framework of flow and transport in the Delta, we do not intend to present an exhaustive list of recent publications.

This paper is organized by the primary drivers of flow and transport in the Delta: ocean, fluvial, anthropogenic, atmospheric, and biogeochemical. Our intent is to present new discoveries rather than a conceptual model of flow and transport. Conceptual models available elsewhere include flow (Monsen et al. 2007; Sridharan 2015) and sediment transport (Schoellhamer et al. 2012). Though we do not present a conceptual model, a conceptual framework for the drivers that determine flow and transport within and through the Delta is presented in Figure 1. We also discuss interactions of multiple drivers and information gaps.

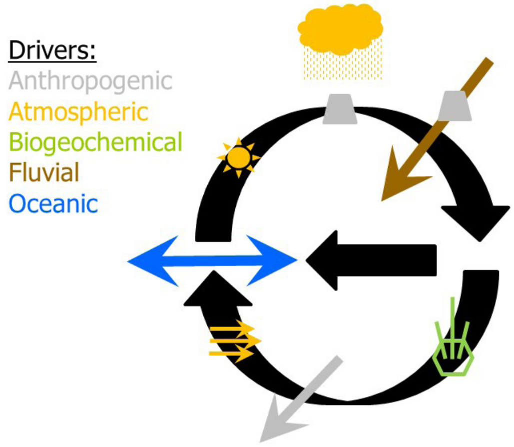

Figure 1 Conceptual framework for drivers of flow and transport in the delta. The black arrows represent flow and transport within and through the delta. Anthropogenic drivers depicted in gray are dams, barriers in the delta, and water exports. Atmospheric drivers depicted in yellow are storms, solar radiation, and wind. Other drivers depicted are biogeochemical processes in green, fluvial inputs in brown, and oceanic exchange in blue.

Other papers that comprise the State of Bay–Delta Science 2016 cover the geographic setting and some specific flow and transport topics in detail, and, thus we minimally include those topics. The geographic setting of the Delta is presented elsewhere in this issue (Healey et al. 2016). Numerical modeling of hydrodynamics and transport in the Delta has greatly advanced in the past 10 years, and is a key tool for testing hypotheses and planning management actions. The numerical modeling paper (MacWilliams et al. 2016) discusses these advances in detail. Movement of fish in the Delta is affected by water flows and is a key management concern. Fish movement is presented elsewhere in this volume (Moyle et al. 2016; Perry et al. 2016).

FLOW AND TRANSPORT DRIVERS

Oceanic Forcing

The Pacific Ocean, via the bay, affects the Delta by propagation of tides, salinity intrusion, and sea level.

Tides

The Bay–Delta is a classic example of a coastal plain estuary in which terrestrial freshwater mixes with salt water entering the estuary from the ocean. The primary agent for this mixing is energetic tidal motions (Fischer et al. 1979) forced by propagation of ocean tides into the Bay–Delta (Cheng et al. 1993). At the western end of the Delta, tidal currents are generally 10 to 100 times larger than tidally averaged currents (see Figure 2; Oltmann 1998). Accordingly, in much of the Delta, tides generally cause the instantaneous currents experienced by organisms, sediment erosion, and deposition (Brennan et al. 2002), and vertical turbulent mixing important for example, to phytoplankton dynamics (Jones et al. 2009).

The flow leaving the Delta past Mallard Island and entering the bay is central to regulations of flow and water quality. Direct measurement of Delta outflow has proven to be difficult, so two methods have been used to estimate outflow. The first is the hydrologic balance embodied in Dayflow[1] and the second is to sum the flows measured by four key USGS flow stations (Oltman 1998). Figure 3 compares two flows for water years 2008–2014. Overall, the comparison is quite good, with a slope near 1, $r^2 = 0.92$, and an RMS error of 6.4 Kcfs. On the other hand, if one examines only low flows, here defined as Dayflow ≤ 10 Kcfs, then there is almost no relation between the two flows ($r^2 = 0.10$; RMS error = 5.1 Kcfs). Thus, at times when the need is most critical to know what

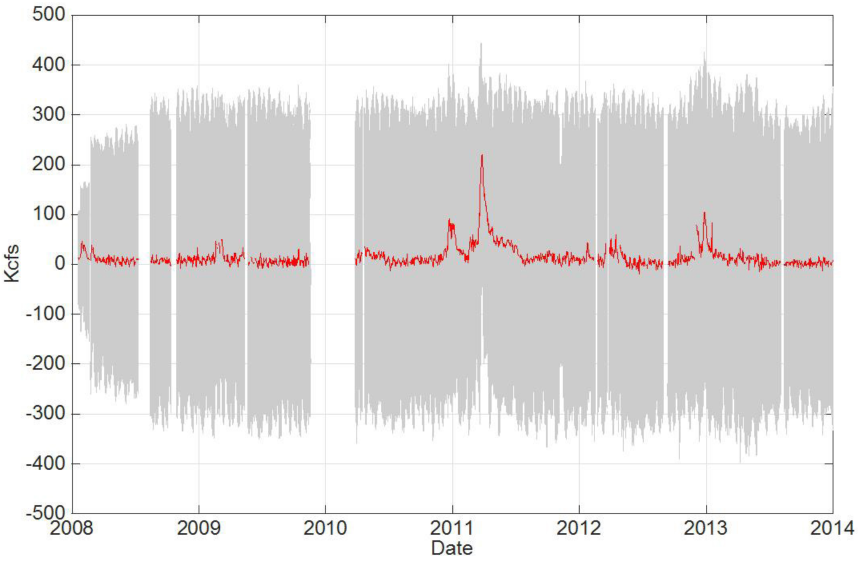

Figure 2 Tidal (grey) and tidally-averaged (red) flows at Mallard Island inferred from USGS flow stations at Rio Vista, Jersey Point, Threemile Slough, and Dutch Slough

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[1] See *http://www.water.ca.gov/dayflow/documentation/dayflowDoc.cfm#Introduction*

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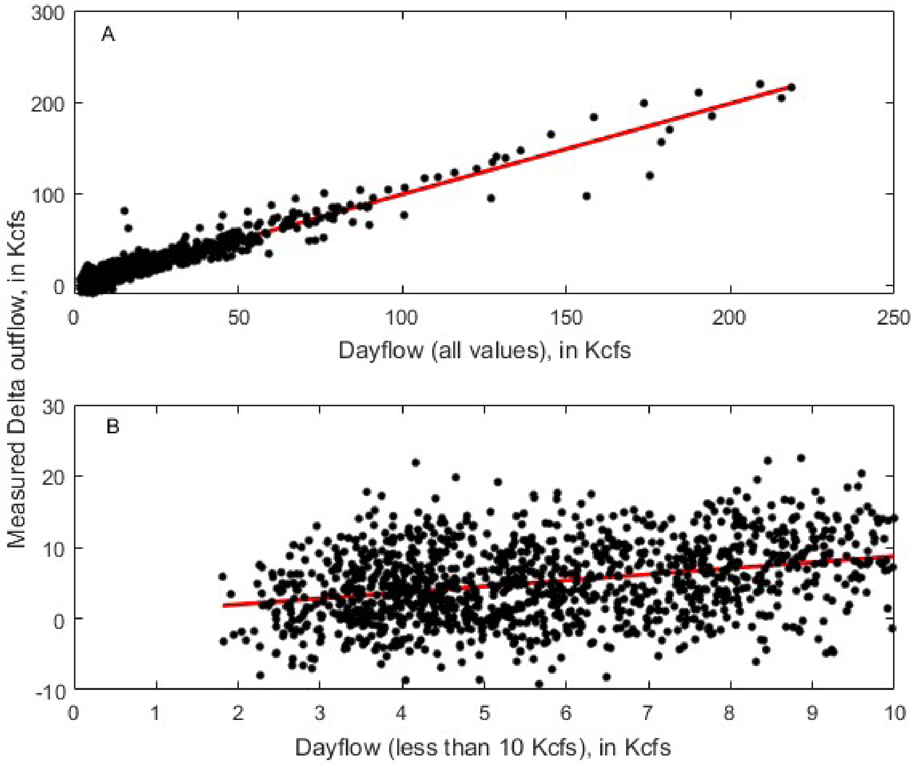

Figure 3 Delta outflow derived from U.S. Geological Survey (USGS) measurements at four stations (points) as a function of California Department of Water Resources (CDWR) Dayflow estimates of Delta outflow for water years 2008–2014 in thousands of cubic feet per second (Kcfs). The top panel **(A)** is for all flows and the bottom panel **(B)** is for Dayflow values less than 10 Kcfs. Least square linear regression lines are shown in red. For all Dayflow values $r^2 = 0.92$ and for Dayflow values less than 10 Kcfs $r^2 = 0.10$. USGS and CDWR data from *http://cdec.water.ca.gov/*.

outflow is, so as to properly manage project (and gate) operations, the uncertainty is very large.

Tides also provide much of the frictional resistance to the mean tidally averaged flow in the Delta. It is this frictional resistance that ultimately determines patterns of mean flow. For example, even though total freshwater flow toward the pumps is set by pumping rates, the spatial distribution of those flows is controlled mainly by the resistance of the different routes by which freshwater can reach the pumps. Fong et al. (2009) show one way in which this behavior might affect Delta-scale transport: They found that because of bedforms, flows through Threemile Slough experience larger drag for flows from the San Joaquin to the Sacramento than vice versa. This should translate into a stronger tidally averaged flow from the Sacramento to the San Joaquin than would occur were the drag symmetric for flow direction. Consequently, the effect of asymmetric friction should be to shift a larger fraction of the overall outflow through Threemile Slough rather than through more northern channels such as Georgiana Slough.

Parameters that quantify a physical, chemical, or biological constituent of the aquatic environment may be misrepresented by low frequency data that fail to observe tidal variations (Lucas et al. 2006). To better understand biogeochemical processes, newly developed optical instruments of various types have been deployed in the Delta and upstream. The new instrumentation can make unattended measurements *in situ* fairly frequently (e.g., every 15 minutes). This capability is particularly important in a tidal setting where tidal advection and dispersion continuously affect constituent concentrations. For example, Ganju et al. (2005) and Downing et al. (2009) used data from Browns Island to assess the minimum sampling frequency necessary to accurately calculate advective and dispersive fluxes in a tidal wetland. That frequency was on the order of three per hour.

The shape of the tidal wave changes as it propagates upstream into the Delta, which creates tidal asymmetry and retains sediment in some parts of the Delta. Morgan–King and Schoellhamer (2013) found an estuarine turbidity maximum in the backwater Cache Slough complex created by tidal asymmetry (peak flood tide currents are greater than peak ebb tide currents), a limited tidal excursion, and wind–wave re-suspension. During the study, there was a net export of sediment, though sediment accumulates within the region from landward tidal transport during the dry season. Sediment is continually re-suspended by both wind–waves and flood tide currents. The suspended-sediment mass oscillates within the region until winter freshwater flow pulses flush it seaward. The hydrodynamic characteristics within the backwater region—such as low freshwater flow during the dry season, flood tide dominance, and a limited tidal excursion—favor sediment retention. This sediment retention is reflected in the relatively fine bed sediment found in the Cache Slough area in comparison to other regions of the Delta (Marineau and Wright, forthcoming). Relatively high turbidity makes the Cache Slough complex favorable habitat for Delta Smelt (Nobriga et al. 2005). These isolated backwater regions used to be common in the Delta (Whipple et al. 2012) but are now rare because channels in much of the Delta are now interconnected to convey water to pumps or to convey floodwaters to the ocean. Restoration of isolated dead-end channels may help ecosystem restoration.

A concept that has evolved during the last decade is that transport in the Delta is driven more by tidal flow than tidally averaged flow. A longstanding conceptual model of transport in the Delta neglects tidal motions and dispersion; i.e., transport of heat, pollutants and non-motile organisms is determined entirely by advection by subtidal flows. For example, according to this model, mean flows along the Old and Middle River corridor act (among other things) to transport small Delta Smelt to the export pumps, such that restrictions on Old and Middle River flows can be used to limit entrainment (Kimmerer 2008). The basis for this assumption is that dispersion in the tidal channels is likely to be relatively weak (Fischer et al. 1979; Ho et al. 2008), and that the effects of tidal motions average out, leaving net motions as the only mechanism for net advection. On the other hand, studies of dispersion in the Delta using numerical models show that dispersion associated with tidal flows through the many junctions of the Delta can be substantial (1995 personal communication between E. List and SGM, unreferenced, see “Notes”; Monsen 2000; Sridharan 2015). The reason for this is that splitting flows at junctions drives what Ridderinkhof and Zimmerman (1992) describe as “chaotic mixing.” Observational evidence for this behavior was provided by Monismith et al. (2009) who suggested that the large heat fluxes out of the San Joaquin system required to close the overall heat balance could be accounted for with remarkably large dispersion coefficients such as those that typify chaotic mixing.

The practical consequence of strong Delta-scale dispersion is that overall transport of constituents through the system may differ significantly from what might be expected in the absence of dispersion; in particular, patterns and rates of organism entrainment at the export pumps might not be simply related to tidally averaged flow patterns. Thus, numerical models of transport used to inform policy must correctly represent the mixing effects of junctions. The challenge of this task is demonstrated by the complex flow behavior seen at the Mokelumne River–Georgiana Slough junction described by Gleichauf et al. (2014) (see also Gleichauf 2015). Tidal flows through this junction produce fronts (regions of separation) and secondary flows, both of which can significantly affect the paths taken by materials and organisms that pass through the junction (Figure 4). Nonetheless, as seen in modeling presented in Wolfram et al. (2016), on average, tidally varying flow trajectories produced by a well-resolved, 2-D, depth-averaged circulation model agreed well with the results of a high-resolution, non-hydrostatic 3-D model, suggesting that practical 2-D models might provide sufficiently accurate representations of junction flows to calculate large-scale transport. In contrast, 1-D models in common use (e.g., Kimmerer and Nobriga 2008) that assume complete mixing at junctions can significantly err in predictions of large-scale dispersion in the Delta, as well as in the

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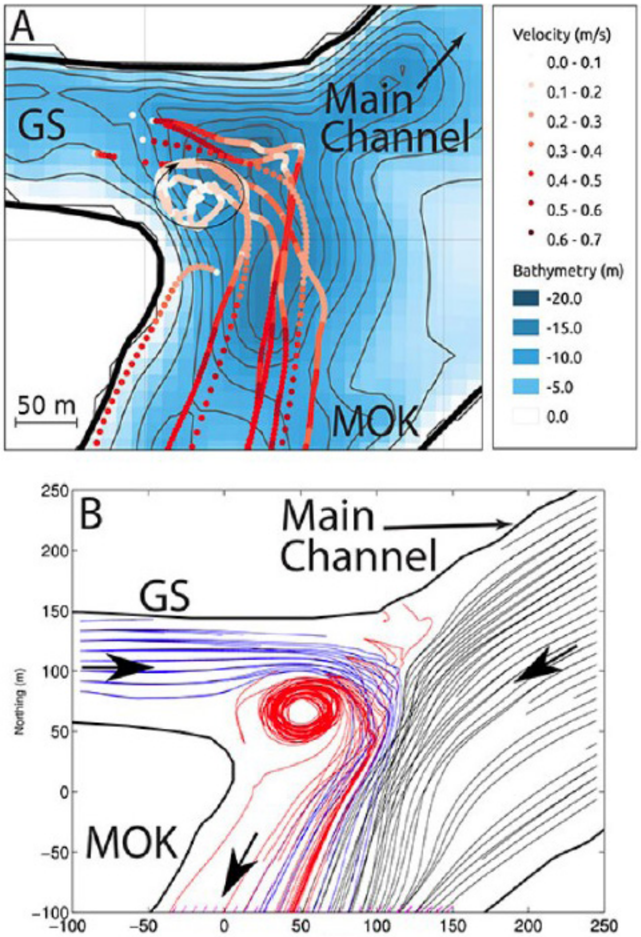

Figure 4 Drifter paths (A) and SUNTANS streamlines (B) reveal a recirculation zone at the west junction of Georgiana Slough (GS) and the Mokelumne River (MOK). Source: Gleichauf et al. (2014).

timing and rates of entrainment at the export pumps (Sridharan 2015).

Salinity

Freshwater flow affects the position of the low-salinity zone (LSZ) in northern San Francisco Bay, which is important habitat for many fish species (Kimmerer et al. 2013). The landward extent of salt from the ocean is determined by freshwater flow (Q) into the estuary. To control the landward extent of salinity, regulations require that Q be adjusted to achieve a desired distance a salinity of 2 is from the Golden Gate Bridge (X2) (Jassby et al. 1995). Given how strongly X2 regulations affect water supply, forecasting how X2 depends on Q is an important component of project operations. Analysis of the flow and salinity data from 1967 to 1991 (Jassby et al. 1995; Monismith et al. 2002) suggested that the time-scale of X2 response to flow is approximately 2 weeks, and that at steady flow X2 is proportional to $Q^{-1/7}$—behavior that Monismith et al. (2002) suggest reflects the effects of tidally varying stratification on turbulent mixing, and hence the transport of salt by gravitational circulation. Using a synthesis of numerical modeling and analysis of more recent observations, MacWilliams et al. (2015) argue that: (1) the response of X2 is fast when Q is large, and slow when Q is small; and (2) the dependence of X2 on Q is $Q^{-1/4}$—behavior that would be predicted from the classical theory of gravitational circulation accounting for actual variations in width and depth of the estuary. MacWilliams et al. (2015) also point out the central challenge of predicting X2 when Q is small: during lowflow conditions, uncertainty in Q can be larger than Q itself. They advocate using a numerical model to define the low-flow X2–Q relation and then (if necessary) using observed X2 variations to infer flow.

Note that both the Jassby et al. (1995) and MacWilliams et al. (2015) models imply symmetrical responses of X2 to flow increases and decreases. In contrast, Chen (2015) showed that the response to flow increases is much faster than the response to flow decreases, in essence reflecting that response time depends on the state of the estuary (X2) as well as on the flow. Monismith (in press) used this idea to construct and validate an X2 model in which the rate of change of X2 is proportional to the difference between the current value of X2 and the equilibrium value of X2 based on the current value of Q. Since this latter model is based on the governing equations, rather than being purely empirical, it may be viewed as preferable from a theoretical standpoint. On the other hand, in practical terms, the physics-based model has quite similar accuracy to the time-series model (Figure 5). That said, one practical consequence of the asymmetrical model is that it implies that pulsed flows require a larger volume of water to maintain a given average value of X2 than does the steady flow that corresponds to that average value of X2.

Observations of salinity in the main channel of northern San Francisco Bay show that depth-

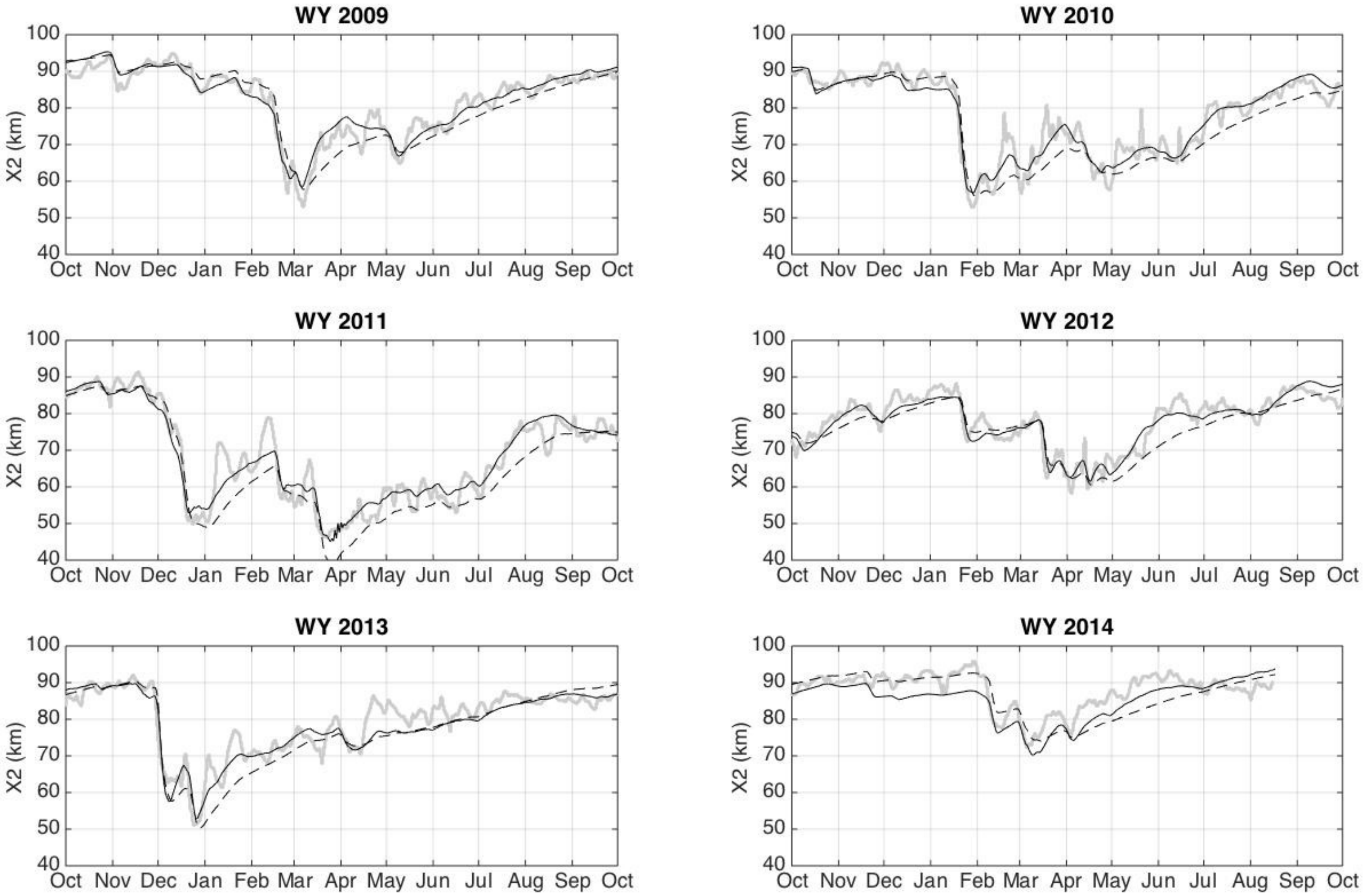

Figure 5 X2 for 6 water years derived from USGS–USBR–CDWR fixed station CTD data (solid grey line) and as predicted by the MacWilliams et al. (2015) time series model (dashed line) and the Monismith (forthcoming) model (solid black line)

averaged salinity depends primarily on the distance of a given point in the estuary relative to X2 (Monismith et al. 2002). Measurements of X2 during the fall of 2011 (Stacey et al., in prep.) show that salinities in Honker and Grizzly bays tend to be lower in general than in the main channel, and respond more slowly to changes in flow and spring–neap variations in tidal mixing that also produce variations in X2 (Monismith, forthcoming).

Sea Level Rise

In addition to tides and salt, future sea level rise (SLR) will propagate into the Delta. Both the salinity field and tidal motions are the result of interaction of the Bay–Delta with physical forcing that itself varies in time. Outflow of freshwater from the Delta, the key factor that suppresses upstream propagation of salt, will likely change in the future because of changes in precipitation patterns caused by anthropogenic climate change (Cloern et al. 2011). At the same time, SLR is expected to have two effects: (1) gravitational circulation will be stronger when channel depths are larger, increasing upstream dispersive salt fluxes so the outflow required to maintain a particular value of X2 will be larger than it is now (Chua and Xu 2014); and (2) because of the likely flooding of large flat areas adjacent to the current Bay–Delta, frictional damping of tides will be stronger, and so tidal propagation through the system will likely change (Holleman and Stacey 2014). We note that this latter effect has not yet been investigated for the Delta itself—Holleman and Stacey's modeling did not include the Delta. Sea level rise will also influence

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water diversions. Wang et al. (2011) simulated future water diversions from the Delta and found that at the end of the 21st century salinity intrusion from SLR of 61 cm will reduce the amount of freshwater available for water diversions.

Swanson et al. (2015) developed a Delta marsh elevation model and found that the magnitude of SLR over the next century was the primary driver of marsh surface elevation change. They defined marsh accretion parameters to encapsulate the range of observed values over historic and modern time-scales, based on measurements from four marshes in high- and low-energy fluvial environments. In addition, they modeled possible future trends in sediment supply and mean sea level. They also conducted a sensitivity analysis of 450 simulations that encompassed a range of porosity values, initial elevations, organic and inorganic matter accumulation rates, and SLR rates. More than 84% of the scenarios resulted in sustainable marshes with a moderate 88 cm of SLR by 2100, but only 32% and 11% of the scenarios resulted in surviving marshes when SLR was increased to 133 cm and an upper bound of 179 cm, respectively. Sediment supply was the next most important controlling factor.

FLUVIAL FORCING

The Sacramento River is the primary source of freshwater flow and sediment to the Delta. Wright and Schoellhamer (2005) found that, for the period from 1999 to 2002, the Sacramento River supplied approximately 85% of the water and sediment to the Delta. The second-largest source, the San Joaquin River, supplied about 12%, with the remaining supply from smaller tributaries such as the Cosumnes and Mokelumne rivers. The Sacramento and San Joaquin rivers both have USGS stream gages that have been in operation since 1957 measuring daily discharge and suspended sediment load (114447650 Sacramento River at Freeport and 11303500 San Joaquin River near Vernalis). Over this time-period, the average discharge and sediment loads on the Sacramento River were about 23,000 ft^3/s and 5,400 tons/day (note: this does not include the Yolo Bypass); on the San Joaquin River, these averages were about 4,800 ft^3/s and 900 tons/day. This suggests that the period from 1999 to 2002 roughly represents at the long-term averages, and that the Sacramento River supplies about 85% of the freshwater flow and sediment to the Delta. The majority of the sediment supply occurs during the winter wet season, typically between December and April. During 1999 to 2002. Wright and Schoellhamer (2005) calculated that 82% of the sediment supply occurred during the wet season, which constituted 31% of the total time Climate change will alter future discharge to the estuary. Cloern et al. (2011) simulated two warming scenarios, one with curtailed greenhouse gas emissions and one with continually increasing emissions. The scenario with curtailed emissions featured statistically insignificant decreases in precipitation and runoff from 2010 to 2099; the increasing emission scenario had statistically significant decreases in both. Both scenarios had statistically significant decreases in percentage of runoff that was snowmelt.

Dams

Dams and reservoirs in the watersheds draining to the Delta have affected the timing and magnitude of freshwater flows and sediment loads. In particular, sediment trapping in reservoirs has strongly affected sediment supply to the Delta. Reservoirs in the Delta watershed capture and store rainfall and snowmelt runoff for a variety of purposes, leading to changes in the flow hydrograph downstream from the dam. These changes typically take the form of decreased peak flows and elevated flows during other times of the year (Singer 2007). However, extreme flooding events still occur in the watershed (for example, 1986, 1997) because of areas of unregulated runoff as well as spills from reservoirs during periods of very high inflow. These extreme events are flood-managed in the valley, downstream from the reservoirs, by a series of weirs and bypass channels (such as Yolo and Sutter bypasses, Singer 2007; Singer and Aalto 2008).

The dams affect sediment supply more than flow, because the larger reservoirs capture approximately 100% of the incoming sediment load, releasing clear water and thus decreasing the downstream sediment supply. The two largest reservoirs in the Sacramento River watershed, Shasta Lake on the upper Sacramento River and Lake Oroville on the Feather River, capture runoff and sediment from large mountainous areas that were likely large sources of sediment to the Delta pre-dam (some portion was also likely deposited in the Valley). Reservoir sedimentation is one factor that contributes to the approximately 50% decline in Sacramento River sediment loads since stream gaging began in 1957 (Wright and Schoellhamer 2004). In the present condition, the primary sources of sediment to the Valley floor and Delta are the largely unregulated Sacramento River tributaries in the northern Valley, that enter the Sacramento River downstream from Shasta Dam (such as Cottonwood Creek, Cow Creek, and Elder Creek). Singer and Dunne (2001), as well as analyses of unpublished data from recent turbidity monitoring along the mainstem Sacramento, indicate that sediment runoff is generated in these areas during intense rainfall events, and transported down the Valley by the Sacramento River to the Delta (with some deposition along the way, Singer and Dunne 2001; Singer and Aalto 2008). The Feather–Yuba–Bear watersheds contribute sediment as well; however, it is likely reduced from pre-dam sediment supply. The current-day supply of sediment from the Feather–Yuba–Bear watersheds is a data gap that hinders definitive analysis of sediment sources. That said, the primary source of sediment to the Delta today is likely the Sacramento River watershed between Shasta Dam and the Butte City area.

First Flush

The first major runoff event of the wet season, which typically occurs in the late fall or early winter, is commonly referred to as the “first flush,” and has particular significance in the Delta. For sediment transport, this event typically has the highest suspended-sediment concentrations, and results in a rapid change in turbidity throughout the Delta (Figure 6, Wright and Morgan 2015). The underlying mechanism responsible for this is sediment supply limitation. During dry periods, landscape disturbances increase the supply of sediment available for transport during runoff events. As the wet season progresses, sediment supply is gradually depleted, leading to decreased peak sediment concentrations (for the same discharge).

Notably, first flush sediments are typically high in associated contaminants and organic carbon (Bergamaschi et al. 2001; Hladik et al. 2009). Hladik et al. (2009) noted that suspended contaminant concentration was highest proximate to agricultural areas, but tended to be lower in the mainstem of the San Joaquin River. Likewise, toxicity was found to be higher in agricultural areas (Weston et al. 2008). Weston et al. (2014) studied pesticides in Cache Slough and found no pyrethroids during the dry season, but pyrethroids were toxic to a test organism after storms. Urban and some agricultural runoff into Ulatis Creek, a tributary of Cache Slough, was responsible.

There is also concern about the ability of sediments to transport mercury to the Delta during first flush. Elevated concentrations of mercury in suspended sediments have been reported (Domagalski et al. 2004; Roth et al. 2001). The concern is that these sediments will be deposited in reducing environments such as wetlands (Bergamaschi et al. 2012) where the mercury will be transformed into its organic and more toxic form: methylmercury (Bergamaschi et al. 2011).

Increases in Delta turbidity during the first flush event have been linked to Delta Smelt habitat, migration, and entrainment at export pumps (Moyle et al. 2016). During first flush in the lower Sacramento River, Delta Smelt migrate landward using lateral differences in tidal currents and turbidity (Bennett and Burau 2015).

During storms, when order-of-magnitude changes in concentration can occur in a matter of minutes, high-frequency sampling is necessary. Importantly, these variations are not necessarily in concert with variation in other parameters such as total suspended sediment. Saraceno et al. (2009), working in Willow Slough, a tributary of the Sacramento River, found that the peak in dissolved organic carbon associated with the storm did not align with either the peak in the hydrograph or the peak in TSS, consistent with their different sources (Florsheim et al. 2011; Oh et al. 2013).

Even for steady flows in rivers, sampling at high frequency may be necessary for chemical constituents with multiple sources or ones that are reactive in the environment. Pellerin et al. (2009) showed that nitrate loads calculated in the San Joaquin River using traditional methods can under- or over-estimate the true load by more than 30% because of

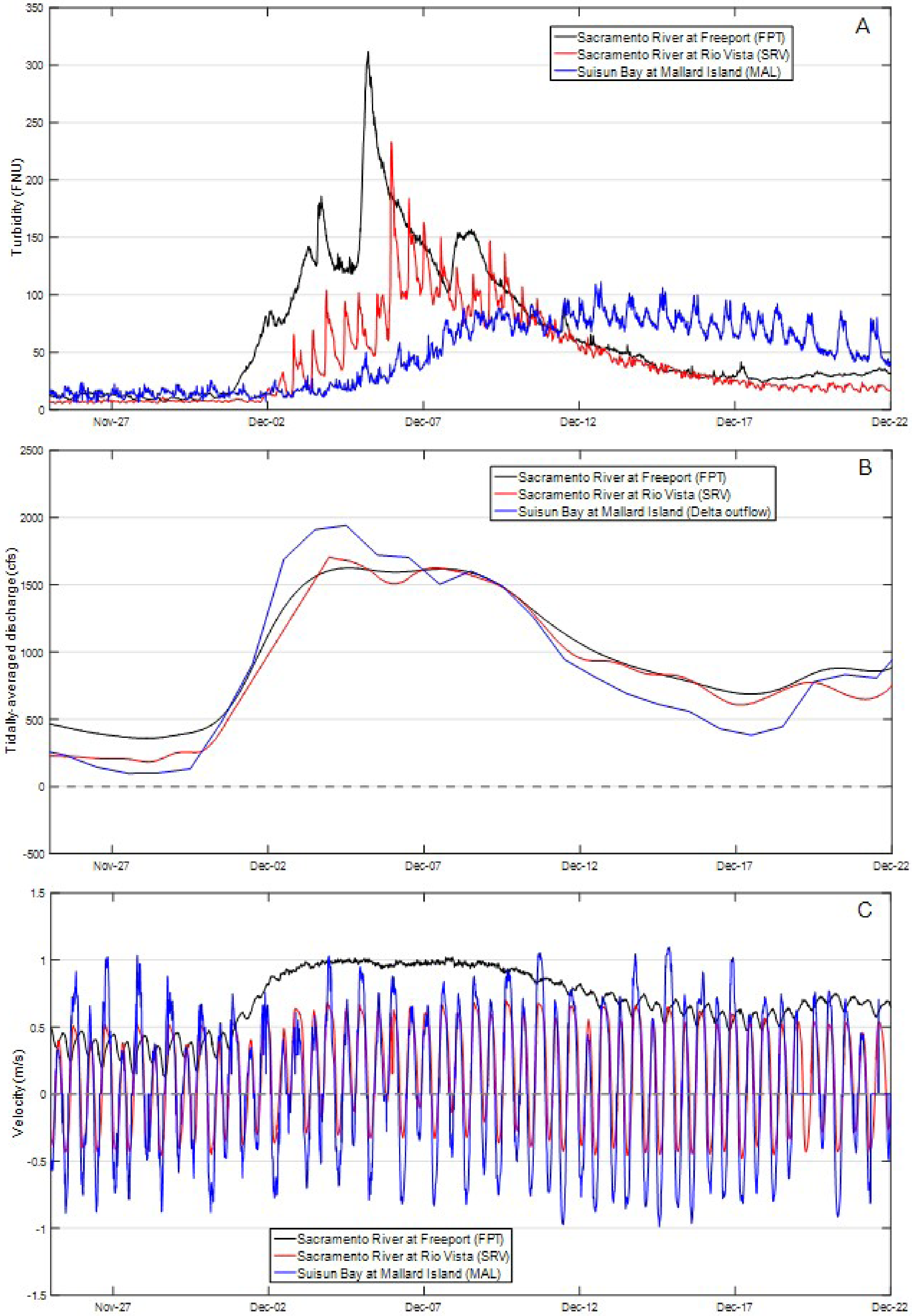

Figure 6 First flush along the mainstem of the Sacramento River in 2012. Turbidity (A), tidally-averaged discharge (B), and velocity (C). Turbidity varies with discharge at Freeport upstream from the Delta. Dispersion decreases the peak turbidity in the downstream direction. Travel time and bidirectional flow in the Delta delay the arrival of turbidity at Rio Vista and Mallard Island. Source: Wright and Morgan (2015).

variation in the nitrate concentration. A sampling frequency of approximately four per hour was necessary to accurately calculate loads and resolve sources.

Sedimentation

By definition, the Delta is a depositional environment for sediment. Deposition of sediment and organic matter contributes to building tidal wetlands in the Delta since the most recent sea level lowstand. The modern sediment budget of the Delta was evaluated by Wright and Schoellhamer (2005) and Morgan–King and Wright (2015), based on high-frequency monitoring of suspended sediment loads at a network of stations in the Delta. For the period from 1999 to 2002, Wright and Schoellhamer (2005) computed the total incoming suspended sediment load to the Delta to be 6.6 ±0.9 million metric tons (Mt) and the total outgoing sediment load to be 2.2 ±0.7 Mt, resulting in 4.4 ±1.1 Mt of sediment deposition over the 4-year period (about 67% of the incoming load). Bed load is approximately two orders of magnitude less than suspended load (Schoellhamer et al. 2012). The magnitude of deposition in the Delta can also be roughly evaluated over a longer time-period. McKee et al. (2013) computed sediment loads at Mallard Island (the downstream boundary of the Delta) for the period from 1995 to 2010, and incoming sediment loads are also available for this time-period for the Sacramento River (USGS Freeport gage) and San Joaquin River (USGS Vernalis gage). The missing piece of information for this time-period is the sediment load coming from the Yolo Bypass, which was found by Wright and Schoellhamer (2005) by using data from 1957 to 1961 and 1980 to be about 28% of the load at Freeport for 1999 to 2002. If the Yolo Bypass inputs are ignored, the average magnitude of deposition from 1995 to 2010 was 60%; if Yolo Bypass inputs are assumed to be 28% of Freeport loads, this magnitude increases to 67%. This suggests that the modern, decadal-scale sediment budget of the Delta is such that about 60% to 70% of the incoming suspended sediment is deposited within the Delta. This percentage varied from year to year, with a low of 39% in water year 1995 (a wet year, 1.63 Mt of deposition) and a high of 88% in Water Year 2007 (a dry year, 0.91 Mt of deposition). From 1995 to 2010, Water Year 1996 had the greatest depositional mass (4.53 Mt, 82%) and Water Year 2008 the least (0.27 Mt, 56%).

Morgan–King and Wright (2015) used a more extensive monitoring program to evaluate sediment budgets within the Delta for 2011 to 2013 for specific regions: the north Delta, central Delta, and south Delta. In general, the south Delta tends to have the highest trap efficiency (fraction of incoming sediment that is deposited), because the south Delta tends to be dominated by tidal forcing. In contrast, the north Delta tends to have the lowest trap efficiency, even though the incoming sediment load to the north Delta is by far the highest. This is because the Sacramento River can be dominated by fluvial forcing during high flows such that large amounts of sediment are passed through this region under these conditions. The central Delta tends to experience the most variability in deposition, primarily depending on upstream conditions in the Sacramento and San Joaquin rivers. During high flows, sediment loads into the central Delta through Georgiana Slough and from the San Joaquin River can be large, resulting in high deposition rates. In 2011, which was a relatively wet year, about 50% of the sediment that entered the central Delta was deposited (the highest among the three regions), whereas in 2012, which was a relatively dry year, only about 23% of the incoming sediment was deposited. This illustrates that the central Delta sediment budget depends on the upstream sediment supply.

Particles are not limited to inorganic sediment, and include plankton. Turbulence affects whether particles will remain suspended and susceptible to transport. Thus, turbulence affects the time plankton remain productive in the photic zone and whether this material will be intercepted by benthic grazers such as clams (Lehman et al. 2009; Lucas and Thompson 2012).

Freshwater flow from the Delta enters and affects San Francisco Bay. Larger Delta outflow can freshen central San Francisco Bay, and the resulting density difference flushes south San Francisco Bay, exporting sediment (Figure 7, Shellenbarger et al. 2013). When Delta outflow is small, central San Francisco Bay remains salty, there is little density difference between the central and south bays, and tidally averaged sediment transport is landward. Sediment

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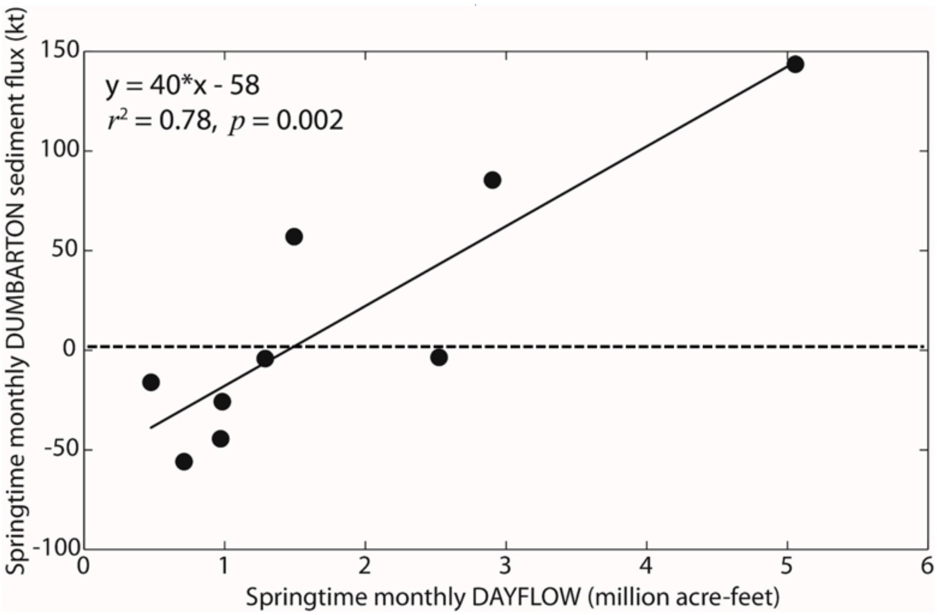

Figure 7 Springtime monthly seaward sediment flux at the Dumbarton Bridge as a function of Delta outflow. Data are for April, May, and June 2009–2011 (Shellenbarger et al. 2013)

supply for the South Bay Salt Pond Restoration Project, the largest tidal wetland restoration project on the west coast of the United States, depends on salinity conditions created by Delta outflow. This demonstrates the dependence of south bay flushing and water quality on Delta outflow, first recognized by McCulloch et al. (1970).

Improved estimates of the historical supply of freshwater and sediment from the Central Valley watershed to the Delta and bay have been developed. Moftakhari et al. (2013) used tidal water level data recorded at San Francisco and tidal theory on the interaction of tides and river discharge to estimate discharge from 1858 to 1929. They found that the annual flow is now 30% less than before 1900, and confirmed that the flood of January 1862 was the largest since 1858. Moftakhari et al. (2015) used measurements of Sacramento River water level to extend this discharge record back to 1849. They also used historical sedimentation data to estimate a time-series of sediment supply for 1849 to 1929. About 55% of the sediment delivered to the estuary between 1849 and 2011 was the result of anthropogenic alteration in the watershed that increased sediment supply. Hydraulic mining in the Central Valley watershed created an initial pulse of sediment and, subsequently, urbanization in the San Francisco Bay Area increased agricultural land use, and forestry practices may have increased sediment supply. Sediment supply decreased about 50% since the 19th century, and the fraction of sediment delivered during winter has increased while the fraction delivered during spring has decreased, mimicking discharge patterns.

Since about 1900, the Central Valley watershed and Delta appear to be geomorphically adjusting as sediment supply from the watershed has decreased (Schoellhamer et al. 2013). Hydraulic mining from the mid-1850s to the mid-1880s created a pulse of sediment and aggradation, which was followed by a period of decreasing sediment supply and degradation. The period of adjustment from decreasing sediment supply may have ended about 1999, resulting in a stable regime. Hestir et al. (2013) analyzed monthly total suspended solids concentration data from the delta from 1975 to 2010 and found that large floods in 1983 and 1998 caused step decreases, likely from removal of erodible sediment (Figure 8). From 1999 to 2010 there was a significant decreasing trend in total suspended solids in the Delta, possibly resulting from supply limitation or trapping by aquatic vegetation. Hestir

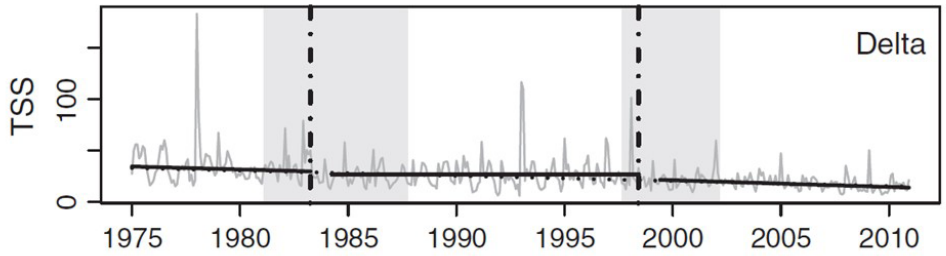

Figure 8 Mean total suspended solids concentration (TSS) in milligrams per liter (mg L^{-1}) from 6 monthly sampling stations in the Delta, 1975–2010, from Hestir et al. (2013). Dates corresponding to a significant break point are indicated with a vertical dashed line. The 95% confidence interval around the break point is represented by the shaded gray area. The solid lines indicate the trends for the periods separated by breakpoints. Before the first breakpoint and after the second decreasing trends were statistically significant ($p < 0.05$). For the period between breakpoints the trend is graphically represented by the mean. Data from *http://www.water.ca.gov/bdma/meta/discrete.cfm*

et al. (2016) found that Delta sites with the greatest cover of submerged aquatic vegetation (SAV) had the greatest decreasing trend of total suspended solids. Schoellhamer et al. (2013) hypothesize that it is likely that the estuary and watershed can still adjust, but further adjustment will be as steps that occur only during greater floods than previously experienced during the adjustment period.

If more precipitation falls as rain rather than snow, creating greater runoff in winter and less in spring, as is the trend (Moftakhari et al. 2015); if storm intensity continues to increase (Russo et al. 2013); if reservoir trapping efficiency does not change; and if there is no more post-hydraulic mining geomorphic adjustment (i.e., erodibility of the watershed does not change, Schoellhamer et al. 2013), then sediment supply to the Delta may increase during the 21st century.

Water Temperature

Water temperatures in the Delta are generally determined by surface heat fluxes (Monismith et al. 2009; Gleichauf 2015) and thus can be well correlated with atmospheric temperatures (Wagner et al. 2011). Inflow temperatures are generally lower than temperatures in the interior of the Delta (Figure 9), so inflows can affect the spatial gradient of water temperature. Wagner et al. argued that any effect of inflows on the overall temperature was only discernible on short time-scales (approximately 1 month or less). On the other hand, large horizontal tidally averaged heat fluxes (of the same scale as diurnally averaged heating in summer) attributed to dispersion were found to be necessary to close the heat balances in the Sacramento Deep Water Ship Channel (SDWSC) at the Port of Stockton (Monismith et al. 2009) and the Delta as a whole (Gleichauf 2015), suggesting that flow-based heat transport may in fact be an important determinant of Delta temperatures.

An interesting aspect of the temperature distribution in 2011 was the seeming importance of cold water entering the Delta from the Merced, Tuolumne, and Stanislaus rivers, i.e., inflows much closer to the Delta than the more southerly sources of the San Joaquin (e.g., Friant Dam). From a management perspective, this suggests that cold water pools in reservoirs closer to the Delta might be useful to

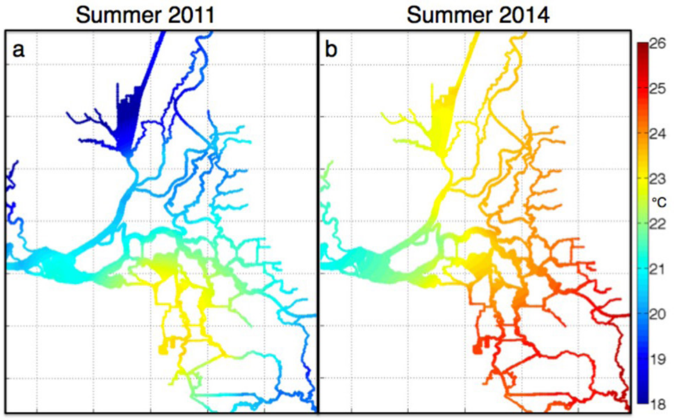

Figure 9 Delta wide average summer temperatures for 2011 and 2014. Source: Gleichauf (2015).

help manage temperatures in the Delta, although this would also require managing the temperature structure in those reservoirs through the judicious use of selective withdrawal (Anohin et al. 2006; Fischer et al. 1979).

ANTHROPOGENIC FORCING

Anthropogenic forcing of the Delta takes a variety of forms, such as (1) changes in volume and timing of Delta inflows (Moftakhari et al. 2013); (2) reductions in sediment fluxes into the Delta (Wright and Schoellhamer 2004); and (3) modification of mean and tidal flows through the operation of pumps, gates, and barriers. We presented the first two topics earlier in this paper; we discuss the later topic below.

Near the upstream end of tidal influence (around Freeport), the Sacramento River divides into several distributary channels, to the east and west of the mainstem. The east-side distributary channel, Georgiana Slough, connects with the lower Mokelumne River and, ultimately, the San Joaquin River in the central Delta. Along with the Delta Cross Channel (DCC), which connects the Sacramento River to the Mokelumne system when its gates are open, Georgiana Slough is the primary pathway for water and sediment to move from the Sacramento River to the central Delta. As shown by Wright and Morgan (2015), this pathway can result in elevated turbidity and sediment concentration in the south Delta, because of the landward net flows in Old and Middle rivers driven by pumping facilities in the south Delta. Once sediment enters the central Delta through the Georgiana Slough pathway, it is gradually advected southward though Old and Middle rivers into the south Delta; Wright and Morgan (2015) calculated a travel time of about 2 weeks from Freeport to the south Delta for a first flush sediment pulse in December 2012. This slow advection of sediment southward, which increases turbidity in the south Delta, has important implications because elevated turbidity in the region of the pumping facilities has been linked to high entrainment of Delta Smelt at the facilities (Grimaldo et al. 2009), which can lead to curtailments of federal and state water deliveries.

Both observations (Gleichauf et al. 2014) and numerical modeling of the Delta (Monsen et al. 2007) show that gate operations significantly affect hydrodynamics and transport patterns in the Delta. When the DCC gate is closed, Sacramento River water reaches the pumps through Threemile Slough and through the confluence region (Monsen 2000; Monsen et al. 2007). Because these transport paths are closer to the higher-salinity waters of the bay, salinities in the western Delta tend to be higher when the DCC is closed than when it is open, so meeting water quality standards in the Delta may require greater outflows into the bay. In a similar fashion, Monsen et al. (2007) show that operation of the Head of Old River Barrier (HORB) may significantly affect residence time in the SDWSC: residence time for particles in the SDWSC were five times smaller when the HORB was in place than when it was absent, a difference that may be important to the formation of hypoxic waters in that reach of the San Joaquin. Finally, it seems likely that tidally operated gates, notably the one in Montezuma Slough, can rectify tidal forcing and thus have significant effects on transport and salinity as well. For example, C. Enright (unpublished manuscript) suggests that when the Montezuma Slough gate is being operated to tidally pump freshwater into Suisun Marsh, it effectively diverts approximately 2500 cfs, possibly a large fraction of the dry-weather Delta outflow (approximately 3,000 to 8,000 cfs) that might otherwise be passing through Suisun Bay.

ATMOSPHERIC FORCING

The water surface is the interface between the atmosphere and Delta waters. Wind can alter Delta water levels and generate wind-generated waves, which can lift material resting on the bottom into the water column. The Delta breeze is the dry season afternoon and evening wind that blows from cooler Suisun Bay through the Delta and into the warmer Central Valley. Heat exchange at the water surface warms or cools Delta waters.

Wind-generated waves enhance sediment re-suspension in some shallow parts of the Delta. Ganju et al. (2005) found that wind wave re-suspension adjacent to Browns Island contributed suspended sediment to the main tidal channel on the island. Morgan–King and Schoellhamer (2013) observed increased suspended-sediment concentrations (SSC) in Cache Slough and the SDWSC (which has a substantial fraction of shallow water) during spring and summer. These increases in SSC were well-correlated with wind speed. Landward sediment flux was greatest during these windy seasons, indicating that sediment retention was enhanced.

Along with wind wave re-suspension of sediments, wind waves also can greatly enhance mixing from wave breaking (Jones and Monismith 2008), an effect in the Delta that is likely to be especially pronounced in the shallow, open-water regions of Franks Tract (Jones et al. 2008) and, presumably, Mildred Island. The enhancement of near-surface turbulence by wave breaking is important in that strong turbulent shears and energetic vertical mixing, both effects of wave breaking, can act to break up colonies of cyanobacteria such as *Microcystis* (O'Brien et al. 2004) and, ultimately, suppress blooms (c.f. Huisman et al. 1999). More generally, wind mixing is important to phytoplankton dynamics in that near-surface turbulence plays a big role in determining the light climate experienced by individual phytoplankton cells (MacIntyre 1993).

Intensity of rainfall increased from 1890 to 2010 (Russo et al. 2013). Data from over 600 precipitation stations in the greater San Francisco Bay area, including the Delta and part of the Central Valley, were analyzed. The intensity of the largest (less frequent) storms increased the most, and a greater fraction of rain fell during large events. More intense storms increase the steepness of runoff hydrographs and increase sediment transport. They may also increase the release of metals from inter-tidal sediments (Moskalski et al. 2013).

Climate change will warm Delta waters. Delta water temperatures are strongly related to air temperature, and not as much to Delta inflow rates (Monismith et al. 2009), so increased air temperatures will warm Delta waters. For scenarios of curtailed and increasing greenhouse gas emissions, Cloern et al. (2011) and Wagner et al. (2011) estimate there will be statistically significant increases in Sacramento River and Delta water temperatures. Delta water temperatures will increases up to 5° C in summer, a change that may prove lethal for Delta Smelt. Given that growth rates for cyanobacteria increase exponentially with temperature (Robarts and Zohary 1987), this temperature rise may also enhance the likelihood of cyanobacterial blooms (Paerl and Huisman 2009). Whether this warming may increase thermal stratification was not evaluated.

Measurements made in the summers of 2004 and 2005 in the SDWSC of vertically varying temperatures show the formation and destruction of diurnal stratification that can be as strong as 2° C from the top to the bottom of the water column (Figure 10, Monismith et al. 2008). This temperature stratification does appear to be dynamically significant, and is the result of turbidity-dependent solar heating and mixing provided by the wind and surface cooling, as well as by turbulence production near the bottom. The practical significance of this stratification is that, given that existing descriptions of the temperature field of the Delta are based on the existing network of sensors, which are largely near-surface, it may be necessary to reconsider the nature of the effects of long-term temperature variability on fish habitat (Wagner et al. 2011; Gleichauf 2015). In particular, it may be possible that there are daytime refugia of colder water that temperature-sensitive fish such as Delta Smelt can use to avoid warmer surface waters. It would be most useful if the existing temperature sensor network were expanded to include near-bottom as well as near-surface temperatures.

BIOGEOCHEMICAL FORCING

Biogeochemical processes within the Delta can alter dissolved substances and suspended particulates. For example, Alpers et al. (2014) studied methyl mercury production in the Yolo Bypass and found methylation produced the highest concentrations in drainage from wild rice fields during harvest, and in white rice fields with decomposing rice straw during flooding. An example of biota affecting transport is invasive SAV in Delta channels. SAV began increasing significantly in the 1970s, and sites that now have greater SAV coverage had a greater turbidity decline in the later 20th century (Hestir et al. 2016). SAV can slow water movement and reduce bed shear stress, promoting sedimentation and reducing SSC. Turbidity trends were corrected for the declining sediment

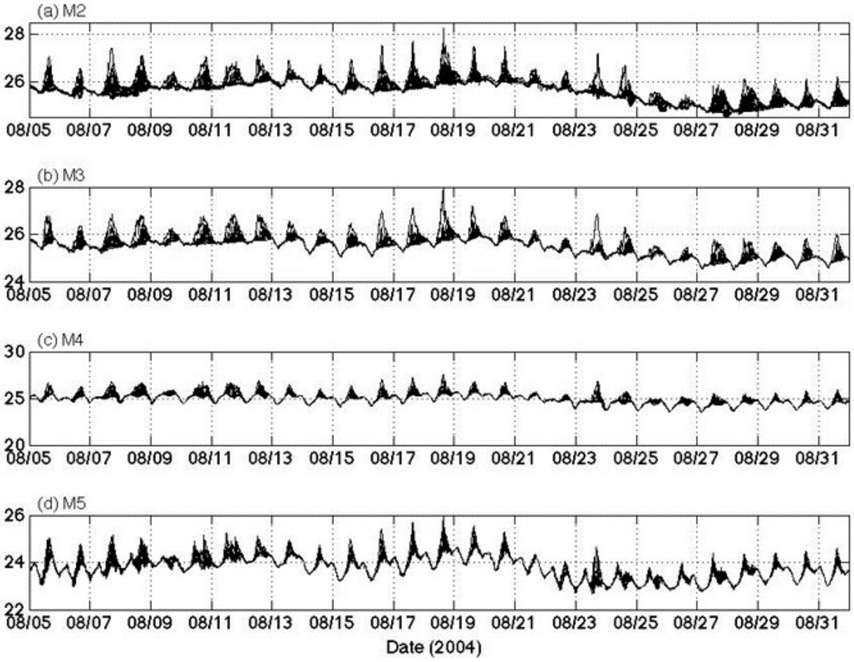

Figure 10 Diurnal variation in temperature stratification at four stations in the Stockton Deep Water Ship Channel. The stations are ordered in the downstream direction and specific locations are given in Monismith et al. (2009). At each station, temperatures were measured at ca. 2m intervals in the vertical.

supply (Wright and Schoellhamer 2004) using SSC data immediately upstream from the Delta. Hestir et al. (2016) estimate that 21% to 70% of the total declining turbidity trend results from SAV expansion.

DISCUSSION

The *State of Bay–Delta Science 2008* (Healey et al. 2008) states:

> … it is now recognized that the twice-daily tides are also extremely influential, causing powerful flow reversals through much of the Delta that amplifies dispersive mixing in both directions. Geometric features of Delta waterways, such as bends, junctions, shallow water areas and levees, all influence water transport and residence times.

Appreciation and consideration of tidal transport and effects were once limited to physical studies, but it has become more common in water quality and ecological studies, and has helped to improve our understanding of these fields (e.g., Bergamaschi et al. 2011; Bennett and Burau 2015).

Interactions of Multiple Drivers

We have summarized the state of the science for flow and transport by the primary drivers: ocean, fluvial, anthropogenic, atmospheric, and biogeochemical (Figure 1). Flow and transport in the Delta are determined by the interactions of these drivers, and management decisions must consider all these drivers.

Drought reduces the effect of fluvial forcing in the Delta and increases the effect of ocean forcing. The drought that began in 2012 decreases sediment supply from the watershed, increases residence times in the Delta, can increase salinity depending on regulation by water managers, and reduces hydrodynamic and salinity variability normally caused by freshwater pulses. Monitoring data sets should be analyzed to quantify the drought's effect on the Delta. The Guadalquivir Estuary in Spain has a similar Mediterranean climate, and drought there increased salinity and displaced communities upstream (González–Ortegón et al. 2015).

Salinity management must consider fluvial, anthropogenic, and ocean drivers. Freshwater flow to the Delta depends primarily on precipitation, snowmelt, and runoff from the Central Valley watershed. Dam operations modify the outflow hydrograph, especially for low flows. In the Delta, gates, barriers, and exports modify flow paths and the salinity field. As sea level rises, ocean forcing in the form of potential salinity intrusion increases. This will require increased anthropogenic forcing to maintain the existing salinity field in the estuary. In other words, ocean forcing in the form of SLR will affect dam operations in the watershed and fluvial forcing on the Delta. Thus, the ocean, estuary, and watershed are linked with one another, and humans have created a feedback mechanism from the ocean to the watershed.

Fluvial and anthropogenic forcing have combined to greatly alter sediment supply to the Delta, and the magnitude of the change is similar to other estuaries. The pattern of human disturbance, increased sediment supply, dam construction, and decreased sediment supply is not uncommon for the Delta. Sediment supply to the Delta increased about an order of magnitude because of hydraulic mining in the late 1800s (Gilbert 1917). Sedimentation rates increased 2- to 10-fold in other California estuaries in the 19th and 20th centuries (Warrick and Farnsworth 2009). These increases are typical of the 5- to 10-fold increase found in lake and marine sediment records downstream from disturbed watersheds (Dearing and Jones 2003). Sediment supply in the Sacramento River decreased about 50% from 1957 to 2001 (Wright and Schoellhamer 2004). This magnitude of decrease is not uncommon; river sediment discharge to the coastal zone has decreased 45% in southern California from trapping behind dams (Warrick and Farnsworth 2009), 50% to 70% from the Mississippi River (Kesel 2003), 75% from the Trinity River in Texas (Ravens et al. 2009), and, globally, riverine sediment discharge to oceans has decreased 10 ± 2% (Syvitski et al. 2005). Reforestation and dams have reduced the sediment discharge in the Changjiang (Yangtze River) 68% from the 1950s to 2000s, and the decrease is expected to reach 82% as dams become fully operational and the system adjusts to them (Hu et al. 2009).

Several mechanisms are responsible for the increasing clarity of Delta waters (Hestir et al. 2013) and clearer waters affect the Delta ecosystem. Decreasing sediment supply from the watershed, floods that export sediment, and sedimentation in SAV beds increase water clarity. Increased water clarity, in turn, may contribute to increased harmful algal blooms (Jassby et al. 2003), SAV expansion (Santos et al. 2009, 2012), and decreased fish abundances (Sommer et al. 2007).

In addition to turbidity, endangered Delta Smelt are affected by water movement, temperature, and salinity. Recent physical advances of significance to understanding and managing Delta Smelt include the ability of backwater sloughs (isolated dead-end channels) to trap sediment and increase turbidity (Morgan–King and Schoellhamer 2013), the possible role of SAV in decreasing turbidity (Hestir et al. 2016), and the role of first flush and tidal currents on their landward migration (Bennett and Burau 2015). Though restoration efforts focus on marsh habitats, backwater sloughs may be an important and scarce habitat for Delta Smelt worthy of restoration.

Marsh restoration is an anthropogenic driver, and its success depends on physical factors such as fluvial sediment supply, a nondestructive wind wave environment, and optimal tidal inundation for plant colonization and growth. Tides, channel geometry, and marsh vegetation may interact to retain sediment in restoration sites. Increasing sediment retention in the Delta would decrease sediment supply downstream to the bay.

Information Gaps

Here, we present what we believe are the most significant information gaps on flow and transport in the Delta, in roughly downstream order.

Though there is general understanding that sediment loads to the Delta have decreased over the past half century, likely from sediment trapping in reservoirs and other factors, the specific drivers of this trend are not understood. In particular, the current and historical watershed sources of sediment to the Delta, and how these sources have changed through time from anthropogenic influences in the watershed, are not understood. Because deposited sediment in the Delta essentially records the history of sediment sources, sediment "fingerprinting," whereby the geochemical signatures of source and sink sediments are examined and linked, could fill this information gap. Changes in watershed sources, such as the elimination of sources upstream from dams, should be reflected in the sediments deposited in the Delta over time, assuming the geochemical signatures of sediments from different regions of the watershed are significantly different. In addition, the current-day supply of sediment from the Feather–Yuba–Bear watersheds is a data gap that hinders definitive analysis of sediment sources.

Water residence time is a key ecological variable that varies tremendously within the Delta. Some channels efficiently transport water and its constituents to the bay or pumps, and some dead-end sloughs have much smaller tidal excursions and longer residence times. Residence time may be particularly significant for the fate and adverse effects of toxic substances. The pristine Delta contained not only much more marsh but many more small dead-end channels, and undoubtedly had regions of longer overall residence time than today's channelized Delta. Additional studies that examine residence time at the regional scale are needed to identify opportunities where increasing residence time improves habitat quality, and pelagic primary production.

To restore pelagic productivity in the Delta, the links between increasing water clarity, nutrient availability, residence time, and phytoplankton production need to be better understood (Cloern 2007; Lopez et al. 2006). Similarly, the relationship between flow characteristics such as velocity and turbulence and the production and sedimentation of organic-rich particles (phytoplankton, phytodetritus, and detritus) has not been well characterized for Delta environments; a mismatch between production and transport may lead to significant attenuation of this carbon supply to lower Delta food webs (Lucas and Thompson 2012).

SAV has increased dramatically in the Delta, particularly in the south Delta, which appears to trap sediment and increase water clarity. SAV, floating vegetation, and decreased sediment supply from the watershed may explain observed decreases in turbidity (Hestir et al. 2016). Given the potential strong feedback between increased clarity and increased SAV, these changes may be an important aspect of the future Delta. Thus, studies are needed to understand the effects of SAV on Delta sediment transport and turbidity.

A question that may be difficult to answer definitively is whether the Delta is now more or less turbid than it was before the Gold Rush when Delta Smelt were presumably more abundant. Dams, deforestation, mining, urbanization, agriculturalization, and river channelization have all changed radically since the Gold Rush, and affect sediment supply to the Delta. Reshaping of the Delta landscape likely altered sediment transport. With no data from before the Gold Rush, numerical models of the watershed and Delta in the early 1800s are likely the best albeit speculative approach to answer this question.

Expanding the existing temperature sensor network to include near-bottom as well as near-surface temperatures would enable monitoring of temperature stratification and near-bottom cooler water that could serve as daytime refugia for fish.

Prevention of salinity intrusion during drought is currently a topic of great interest that also merits additional study to determine how to efficiently prevent intrusion while minimally disrupting the ecosystem. Each barrier placement should be considered an experiment from which analysis of data collected before and after placement and removal would provide lessons for building a better barrier next time.

Uncertainty in low flow values of Delta discharge likely plays a major role in defining the uncertainty in forecasting low flow values of X2. A significant effort to reduce the uncertainty in low-flow values of Delta discharge is needed.

CONCLUSIONS

The tremendous expansion of acoustic and optical instruments deployed in the Delta over the past decade has greatly improved our understanding of how tidal variability affects flow and transport. Low Delta outflows are poorly estimated by a tidally averaged water balance. Water quality sampling that fails to consider tidal variability can bias results. Transport in the Delta is driven more by tidal flow than tidally averaged flow. Mixing at junctions disperses water-quality constituents. Gates and barriers can significantly alter transport pathways. In addition, storms with similar time-scales of hours can supply and transport significant quantities of sediment and water-quality constituents.

Sediment is increasingly viewed as a diminishing resource needed to sustain the Delta ecosystem. Since 2000, the turbidity of Delta waters has decreased at an alarming rate. Native fish, including endangered Delta Smelt, favor turbid waters. Sediment supply is a key variable in determining the sustainability of tidal marsh as sea level rises.

Connections among the watershed, Delta, and the bay that have been quantified recently highlight that a landscape view of this system—rather than consideration of each region in isolation—is often needed. Reservoirs release water to maintain a salinity field in the Delta and bay that allows water diversions, and the volume of water needed to accomplish this will increase as sea level rises. The first flush of the watershed at the beginning of the wet season delivers a pulse of sediment and other constituents that affect the water quality and ecology of the Delta. The timing and magnitude of freshwater discharge from the Delta to the bay determines flushing and transport in south San Francisco Bay.

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