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Sediment Monitoring and Modeling Strategy

On behalf of the San Francisco Bay Regional Monitoring Program Sediment Workgroup

Prepared by

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Executive Summary

Sediment is a basic building block of Bay geography and habitats, acting as the physical foundation for tidal marshes, which must vertically accrete to keep pace with sea-level rise and continue functioning as natural filters for nutrients and pollutants. In 2016, the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) created the Sediment Workgroup (SedWG) to provide technical oversight and stakeholder guidance on RMP studies addressing management and policy needs associated with sediment delivery, sediment transport, dredging, and beneficial reuse of sediment within San Francisco Bay. Since 2016, the SedWG has met once or twice a year, reviewed the current status of information, and recommended a portfolio of special studies and more generally identified monitoring and modeling as two important elements in an overall strategy. Since the SedWG is one of five groups coordinating the study of sediment processes in the Bay Area, we intend for this Modeling and Monitoring Strategy to serve as a foundation document that enables communication and collaboration between these groups.

San Francisco Bay is one of the more complex systems in the world due to the weather patterns from both northern and equatorial latitudes; location within the San Andreas fault zone; receipt of runoff and sediment loads from both the Sierra Nevada Mountains and the coastal range; urban, industrial and maritime history spanning 150 years; and large scale modification of the bathymetry and shoreline. The system is quiescent much of the time but “awakened” by stochastic events that cause large changes in the water and sediment budgets in very short periods of time, such that monitoring and modeling is a difficult enterprise with many remaining limitations and weaknesses. As models and data collection efforts begin to synergistically interact, and remote sensing becomes more common, information development may accelerate.

This strategy document is organized progressively to lay out the rationale and arguments for the higher priority monitoring and modeling recommendations that are found in Section 5. In Section 1 of this strategy, we briefly describe the endeavors of the five groups working on aspects of Bay sediment science as context for the strategy. Then in Section 2, we lay out the management questions developed by the SedWG and compare these to the management questions identified by the San Francisco Bay Conservation and Development Commission and the Wetlands Regional Monitoring Program. In Section 3, we provide a review of the literature describing the basic physiology of the Bay before outlining a basic conceptual model for the Bay system and a means for organizing information. In Section 3, we also provide a summary of what is known about sediment processes in the Bay to provide context for the swath of detailed monitoring and modeling recommendations that are provided in Section 4. Section 5 provides a summary of workgroup decisions on the highest priory information gaps and indicates which of those have already received funding and which are still pending. Once these high priority studies have been funded, recommendations arising from the new information will be considered for funding along with the remaining medium priority information gaps outlined in Section 4. Section 6 provides a reference list.

1. Introduction

1.1 Formation of the Regional Monitoring Program Sediment Workgroup

Sediment is a building block of Bay geography and habitats, and is the physical foundation for tidal marshes, which must vertically accrete to keep pace with sea-level rise and continue functioning as natural filters for nutrients and pollutants borne in urban, agricultural, and industrial runoff sources. In addition, sediment can store contaminants within interstitial waters or adsorbed to particle surfaces, and be a source for their uptake into biota or transport within and out of the Bay. Suspended sediment in the water column also affects water quality, and is a primary limiting factor for photosynthesis and eutrophication. There is a growing focus on sediment processes in the Bay, driven by the need for better information on water and sediment quality, as well as the impacts of climate change and sea-level rise to the Bay's wetlands.

In 2016, the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) created the Sediment Workgroup (SedWG) to provide technical oversight and stakeholder guidance on RMP studies addressing management and policy needs related to sediment delivery, sediment transport, dredging, and beneficial reuse of sediment within San Francisco Bay. The SedWG includes representatives from public agencies, including the U.S. Environmental Protection Agency (USEPA), U.S. Army Corp of Engineers (USACE), U.S. Geological Survey (USGS), San Francisco Bay Regional Water Quality Control Board (SFBRWQCB), and San Francisco Bay Conservation and Development Commission (BCDC), as well as representatives from ports, the in-Bay dredging community, universities, consulting firms, and two independent sediment science advisors.

Since 2016, the SedWG has met once or twice a year, reviewed the current status of information, and recommended a portfolio of special studies that were funded by the RMP using either special studies funding or supplemental environmental projects (SEP) funding, beginning in 2017. The SedWG has, more generally, identified monitoring and modeling as two important elements in an overall strategy for sediment in the context of sediment transport and sedimentation impacts. In addition, the Workgroup reevaluated the management questions driving information needs and identified the need to create an integrated Sediment Modeling and Monitoring Strategy (SMMS) to benchmark current knowledge gaps and devise studies to understand processes, evaluate changes over time, and forecast future conditions. Where possible, the SMMS will emphasize the use of surrogate measures and modeling as cost-saving tools to address management questions.

1.2 Other existing efforts and agencies

The SedWG is not the only group coordinating the study of sediment processes in the Bay Area. Other groups include the WRMP (Wetlands Regional Monitoring Program); BCDC, which has a broad scope based around resource management and permitting entities that make changes to the Bay's morphology; and other RMP workgroups that focus on nutrients and watershed loadings. However, the SedWG is presently the only group that includes management questions that link sediment to contaminant and nutrient processes. Historically, the RMP has mainly focused on fine sediment (mostly silts and clays), processes within the water column, and sediment in the deeper channels of the Bay. This SMMS documents a broadening of the scope and resulting list of management questions considered by the RMP to include all sediment (fines but also sands, and even the less prevalent gravels, and cobbles), bathymetry, and sediment transport processes, not only in the Bay, but also the subtidal shoals, the mudflats, sloughs, and wetlands (generally more inclusion of wetlands and their function).

Given this plethora of groups and activities, the SMMS will need to serve as a foundation document that enables communication and collaboration between subgroups and organizations. Coordination of staff and expertise across these groups will help ensure funding decisions for projects are well coordinated to reduce duplication and speed up information development.

1.2.1 Wetlands Regional Monitoring Program (WRMP)

The WRMP, with a broad oversight committee like the SedWG that includes state and federal agencies and local stakeholder groups, differs from RMP efforts in that it is focused on the intertidal marshes and mudflats. The group came together in 2017 and, through a series of meetings, developed and published a set of management questions (WRMP, 2018). Building from this, a core team completed a San Francisco Estuary Wetlands Regional Monitoring Program Plan (WRMP, 2020). Although the WRMP does not presently (as of November 2020) have stable and ongoing funding or staff, the WRMP Program Plan contains a series of high-level management questions that are used to guide direction and serve as an umbrella for a series of monitoring questions that have associated indicators, metrics, and spatio-temporal monitoring designs:

1. Where are the region's tidal wetlands and wetland projects, and what net landscape changes in area and condition are occurring?
2. How are external drivers, such as accelerated sea level rise, development pressure, and changes in runoff and sediment supply, impacting tidal wetlands?
3. How do policies, programs, and projects to protect and restore tidal marshes affect the distribution, abundance, and health of plants and animals?
4. What new information do we need to better understand regional lessons from tidal wetland restoration projects in the future?
5. How do policies, programs, and projects to protect and restore tidal wetlands benefit and/or impact public health, safety, and recreation?

The detailed monitoring questions and resulting products generated through the WRMP have the potential to overlap with products generated by the SedWG.

1.2.2 Bay Conservation and Development Commission (BCDC)

For decades, BCDC has been coordinating sediment studies in San Francisco Bay that have involved a broader group of people than the WRMP, and has more potential for overlap with the RMP SedWG. Its areas of jurisdiction include overseeing dredging in the Bay and tidal portions of flood control channels, sand mining permits, climate change and sea-level rise adaptation, sediment disposal and reuse, and wetland restoration. In 2010, BCDC and USGS co-hosted a State of Sediment Science workshop that had a broad array of attendees, including scientists and managers. This workshop resulted in the identification of a set of priority data needs for further research and modeling efforts for the Bay and watershed, and garnered support from the research community for continued investigation of sediment management issues. In 2014, BCDC organized a day-long Sand Mining Science Panel to discuss the current knowledge of the Bay's bathymetry, sediment transport, and subtidal habitats in relation to known areas of sand deposits in the Bay. The scientists, consultants, and managers identified data gaps and the need for additional research on San Francisco Bay sediment management and physical processes. In 2015, BCDC conducted a third workshop to identify regional sediment science priorities (BCDC, 2016a). Based on input from diverse workshop participants (representatives from federal, state, and local agencies, non-profits, and consulting firms), the resulting summary report provided a set of key management questions subdivided into three main topics:

- Watershed, Tributaries, and Flood Control
- Marshes and Mudflats
- Beaches and Non-wetland Shorelines

In 2016, BCDC also presented a Central San Francisco Bay Regional Sediment Management Plan (RSM), which contained a series of recommendations for changes to practices and activities to maximize sediment use as a resource, protect sensitive resources, improve the health of the Bay, align management activities, reduce project costs, and help address climate change impacts and other system stressors (BCDC, 2016b). It also included monitoring and data needs on two specific aspects of sediment process:

- Update Bay bathymetric maps to support modeling and sediment budget refinement in the context of shoreline change, dredged material disposal (or reuse) and sand mining permits, and
- Implement additional tributary suspended sediment and bedload sediment monitoring in major channels, tributaries, and in Bay cross-sections (between subembayments) to support modeling marsh accretion rates and Bay sediment transport and refine load estimates from watersheds and other embayments in the context of permitting restoration projects, better management of flood control channels, and (Bay) dredging projects.

BCDC staff also participated in the "Flood Control 2.0" project, which helped refine the bed sediment load estimates for the small tributaries around the Bay (SFEI-ASC, 2016) and subsequently produced (with in-kind support from USGS and SFEI) the first-ever sand budget for the Bay in relation to sand mining activities (Perry et al., 2015). This “draft sand sediment budget” was an important step forward but was challenged by weaknesses in the data sets. As such, BCDC in coordination with the California Coastal Conservancy released a request for proposals in July 2020 to call for contractors to further develop the region’s understanding sand mining’s effects on San Francisco Bay and associated outer coast, the sand budget and transport mechanisms, as well as stratigraphy of the sand beds. The chosen contractors will 1) review and summarize existing sand-transport and related geophysical literature and bathymetric data for the sand mining lease areas and surrounding areas in Central San Francisco Bay and within Suisun Channel, 2) update and refine an existing draft sand budget and database for the San Francisco Bay and adjacent outer coast, 3) conduct stratigraphic sampling in multiple sand mining lease areas in order to characterize the depth and quality of the sand in these lease areas, and 4) assess sand transport in San Francisco Bay and the adjacent outer coast.

In 2021, BCDC will continue its efforts on regional sediment management planning that builds on the Central Bay RSM and the successful Long Term Management Strategy (LTMS) program and seeks to incorporate flood protection, habitat restoration, sand mining, and shoreline erosion in San Pablo Bay, working on other embayments over time for a consistent understanding of sediment management activities.

1.2.3 The Regional Monitoring Program for Water Quality in San Francisco Bay

In addition to the WRMP and BCDC, the RMP has two other workgroups that work on aspects of Bay and watershed sediment science. The San Francisco Bay Nutrient Management Strategy (NMS) is funded by the wastewater treatment facilities that discharge to San Francisco Bay. NMS science staff have been partnering with the USGS since 2013 on a moored sensor program. Turbidity sensors were installed at eight margin and slough locations in Lower South Bay (south of the Dumbarton Bridge). These locations have not been calibrated for SSC, so the opportunity exists to increase collaboration and carry out a turbidity-SSC calibration (see recommendations section).

In addition, the NMS has been working with modelers at the USGS, Department of Water Resources (DWR), UC Davis, UC Berkeley, and Deltares to leverage existing hydrodynamic models and expertise. In 2017, the NMS completed its first thorough hydrodynamic model calibrations for the Bay using Delft3D-FM (DFM), a finite-volume, three-dimensional, unstructured hydrodynamic model (Martyr-Koller et al., 2017). The original model setup was developed by the masters student Silvia Pubben overseen by Mick van der Wegen (Pubben, 2017), as a continuation of prior modeling efforts stemming from the USGS and San Francisco Bay-Delta Community Model projects. The model domain covers San Francisco Bay, including portions of Coyote Creek and Guadalupe River to the south, extending north to the Sacramento and San Joaquin Rivers at Rio Vista and Jersey Point, respectively. The domain also extends into the Pacific Ocean, roughly encompassing the San Francisco Bight. The unstructured nature of the grid allows for efficient and flexible resolution of flow features ranging from small perimeter sloughs to a regional representation of the coastal ocean. The model inputs include tides, direct precipitation, evaporation, stormwater runoff, wastewater discharges, Delta outflow, and wind. From these inputs, the model calculates water levels, salinity, currents, and the force of the currents on the bed throughout the Bay. The 2017 calibration of the model predicted tides, salinity, and freshettes for South, Central, and San Pablo Bays (Holleman et al., 2017). The model predicts tides, salinity, temperature, and freshettes for the Suisun-Delta system but the 2016 calibration year did not encompass the Sacramento Weir opening (King et al., 2019). In 2020, the NMS continued work on the Bay model, making improvements to wind and temperature among other attributes, and modeling nutrient processes in South Bay for water year 2013 including phytoplankton, zooplankton, and sediment detrital nitrogen (SFEI, 2020). This NMS suite of models would be an ideal starting point for modeling Bay sediment dynamics.

The Sources, Pathways, and Loading Workgroup (SPLWG) of the RMP has been working on suspended sediment loads estimates from its inception in 1999. The SPLWG is also composed of scientists, managers, and policy makers from federal and state agencies, local governments, consultants, non-profit organizations, and academic institutions. They have been responsible for developing the first reliable estimates of suspended sediment loads coming into the Bay from the Delta through the tidal cross-section at Mallard Island (McKee et al., 2002) and improving estimates of suspended sediment loads from small tributaries (McKee et al., 2003), with interactive refinements of these through time (McKee et al., 2006; Lewicki and McKee, 2010; McKee et al., 2013). Together these efforts caused a paradigm shift in our perceptions of suspended sediment supply to San Francisco Bay. While sediment loads had previously been assumed to be dominated by supply from the large Central Valley rivers, these studies demonstrated that the trends that had been predicted by Ray Krone in the 1990s had indeed occurred, leading to a Bay dominated by local tributary sediment supply (McKee et al., 2013). Presently, the SPLWG is overseeing a new multi-year effort (2018-2022) funded by the RMP to develop a regional scale hydrodynamic watershed model using LSPC (a C++ re-coded version of Hydrological Simulation Program - Fortran [HSPF]). In relation to sediment, the model will provide new daily estimates of flow and suspended sediment loads from the hundreds of small tributaries within the nine-county Bay Area (Wu et al., 2018; Wu and McKee, 2019; Zi and McKee, in preparation). In parallel, the SPLWG is also leading a supplemental environmental project (SEP)-funded RMP effort to provide additional suspended sediment monitoring data on an four small tributaries (Belmont, Arroyo Corte Madera del Presidio, Novato, and Walnut) with data maturity expected in December 2021 (Gilbreath and McKee, in preparation).

1.3 Strategy goals

The overarching goal of this Strategy is to provide a framework and work plan for monitoring and modeling elements that address the highest priority information gaps regarding sediment processes in the Bay. These monitoring and modeling elements ultimately support the development of related policy and management efforts for San Francisco Bay.

Since only a portion of funding comes from the RMP, the SMMS will help to facilitate the coordination of monitoring and modeling efforts among multiple groups and funding sources. Managing sediment and understanding sediment transport processes within the Bay is integral for maintaining estuarine ecosystems and fostering resilience to future changes in climate, sea-level rise, and urban development. This SMMS was developed to outline the types of monitoring data and modeling information most urgently needed by policymakers and managers to reduce impacts and maximize benefits associated with sediment loading to, and transport and storage within, San Francisco Bay. It will also help the SedWG prioritize modeling and monitoring special studies. Given the size and complexity of the Bay, the RMP will be unable to provide funding for all of the recommendations in the SMMS. As such, the SMMS will act as a road map for coordinated activities with other agencies and organizations, and provide a context for sharing new findings and to avoid duplication of effort. The premise of this strategy is that a well thought out and coordinated effort to fund monitoring and modeling studies will lead to more efficient use of limited funding and more quickly lead to policy and management decisions that will improve water quality in the Bay and increase resilience to sea-level rise.

2. Management Questions

This section provides details about the RMP SMMS management questions and a summary table showing how these compare to the management questions of the other key groups. The efforts of the RMP SedWG are focused on increasing our understanding of sediment processes to inform management practices into the future. These potential management practices fall under two wider geographical restoration types: upland restoration and tidal wetland restoration. Restoration and reshaping of upland habitats outside of the Bay's tidal influence typically require artificial intervention outside of natural sediment transport processes to recontour topography into a functional and ecologically resilient form. Understanding sediment transport mechanisms are less important in these instances. Conversely, tidal wetland restoration can utilize natural processes to mobilize and redeposit emplaced sediment to vertically build marshes, mudflats, and baylands. Consequently, the RMP SedWG places a high priority on processes that will inform management and restoration of tidal wetlands. The workgroup formulated five governing Sediment Management Questions to guide and prioritize future studies on sediment transport processes within the Bay:

1. **What are acceptable levels of chemicals in sediment for placement in the Bay, baylands, or restoration projects?**
   As sea levels rise and both human and wildlife communities are threatened by accompanying high tides and storm surges, it is clear that the marshes and wetlands that attenuate wave energy and filter nutrients and contaminants will need additional sediment in order to maintain their functions into the future. As such, the sediment must be placed in these areas from sources outside of their natural watershed and marine pathways. The potential sources of this sediment are wide-ranging and could contain chemical contaminants that are deleterious to wildlife and humans. As such, it is

important to understand what levels of sediment chemical contamination are acceptable for placement in the Bay, baylands, or restoration sites.

2. **Are there effects on fish, benthic species, or submerged habitats from dredging or placement of sediment?**

   The San Francisco Bay and its subembayments historically supported a rich and unique estuarine ecosystem within its shallows and tidal marshes. Meanwhile, human activity within this ecosystem has included the dredging of sediment, which is necessary to enable local commerce and transportation. As it becomes necessary to build up and restore tidal marshes while also maintaining the local economy, it is important to understand the ecosystem consequences of the removal and strategic placement of sediment.

3. **What are the sources, sinks, pathways, and loadings of sediment and sediment-bound contaminants to and within the Bay and subembayments?**

   In order to inform future Bay management actions, it is important to attain a higher resolution of sediment sources, magnitudes, transport pathways, and sinks across multiple temporal and spatial scales. Sources of sediment for the Bay consist of all bay-draining watersheds above the head of the tide, as well as sediment input from the Delta. Sinks are sites where sediment is stored temporarily or indefinitely, including mudflats at creek mouths, accretionary tidal marshes, deep channels, and the Pacific Ocean outside the Golden Gate Bridge. The largest sediment transport pathways include the Sacramento and San Joaquin Rivers (represented by monitoring at the Mallard Island cross-section), the small tributaries and flood control channels that drain from the nine fringing counties around the Bay (amounting to 300+ channels, creeks and storm drains), the exchange with the Pacific Ocean at the Golden Gate Bridge, net removal by dredging and mining, and net erosion or deposition at the bed or shoreline (Schoellhamer et al., 2005). In addition, there are a series of negligible pathways (atmospheric deposition directly to the Bay surface, municipal and industrial wastewater, and changes in the net mass in the water column). It will be most effective to prioritize studies on the high-magnitude and high-uncertainty sources, sinks, pathways, and loadings within the Bay while keeping in mind their influence on the minor pathways.

4. **How much sediment is passively reaching tidal marshes and restoration projects, and how could the amounts be increased by management actions?**

   Retaining existing and restoring new functional tidal marshes is integral for building resiliency to sea-level rise and fostering a healthy bay ecosystem into the future. The Baylands Ecosystem Habitat Goals Update (Goals Project, 2015) laid out a vision of restoring 100,000 acres of tidal wetlands and how they may evolve with climate change. Meanwhile, funding from the San Francisco Bay Restoration Authority is providing $25M over the next twenty years for marsh restoration, and the Wetland Regional Monitoring Program (WRMP) is developing a pilot program to monitor mature and restored tidal marsh habitat. There is a central question to all these efforts: Is there enough sediment to address restoration objectives? To answer this, we need an increased understanding of processes on mudflats, in feeder channels, and in tidal sloughs. This information must coincide with the run periods of 3D hydrodynamic models of Bay processes.

5. **What are the concentrations of suspended sediment in the Estuary and its subembayments?**

   The goal of this component of the monitoring and modeling plan is to recommend a modeling approach tuned to estimate suspended sediment concentrations (SSC) at temporal and spatial scales of interest to policymakers and managers. SSC and the process of resuspension that maintain or enrich suspended sediment in the water column are key properties of San Francisco Bay. SSC has many effects of interest to managers, including diminished eutrophication, differing stresses and preferences for marine wildlife, and varying potential for sediment deposition.

Of these questions, the first two focus on dredging and sediment placement, sediment quality, and their effects on habitats and species. The other three questions focus on the physics of sediment in the Bay—quantity, movement, and deposition, particularly on tidal marshes—and are the primary questions addressed by this strategy.

These management questions stem from conversations within the Bay restoration community over the last few years, such as BCDC's "The Science of Sediment" workshop (BCDC, 2016a). That workshop developed a series of high priority questions in several categories: watershed, tributaries, and flood control; marshes and mudflats; beaches and non-wetland shorelines; and open bay and subtidal areas. Also, in 2019, the WRMP developed its own management questions that focus on the distribution and condition of wetlands; changes in elevation capital; regional differences in the availability of sediment to wetlands; and the role of management actions such as strategic placement (WRMP, 2018).

Some of these groups' high priority questions cover issues, such as addressing regulatory hurdles and developing shoreline management strategies that are outside the remit of the RMP SedWG. RMP questions 1 and 2 address specifics of dredged sediment use not covered by the BCDC or WRMP questions. Table 1 shows a crosswalk between the questions raised in the BCDC 2015 workshop, the WRMP guiding and management questions, and the RMP SedWG management questions.

Table 1 - Crosswalk between BCDC high priority questions, WRMP management questions, and RMP Sediment Workgroup management questions 3-5

Other groups' guiding questions		**RMP Sediment working group management questions**		
BCDC Science of Sediment workshop high priority questions		**MQ3 - What are the sources, sinks, pathways, and loadings of sediment and sediment-bound contaminants to and within the Bay and subembayments?**	**MQ4 - How much sediment is passively reaching tidal marshes and restoration projects and how could the amounts be increased by management actions?**	**MQ5 - What are the concentrations of suspended sediment in the Estuary and its subembayments?**
Watersheds and tributaries	W1 - How can we design channels to help convey sediment to baylands rather than into the Bay?		✔	
	W2 - What do we estimate to be the change in sediment supply/erosion of our watersheds into the future?	✔		
	W3 - Where can we reuse dredged sediment from channels—nearby, locally, and cheaply?		✔	
	W4 - Could we use multi-criteria decision analysis tools to address sediment management alternatives?		✔	
	W5 - How do we better link our floodplains with our marsh plains?		✔	
Marshes and mudflats	M1 - How can we ...test the modeling results of in-Bay placement naturally redistributing to marsh plain, leading to more efficient "beneficial reuse"?		✔	
	M2 - How and where do/should we assist vertical accretion of marsh/mudflats?		✔	
	M3 - What is the predicted "new normal" for SSC... and how does it vary spatially around the Bay?			✔
Beaches and non-wetland shorelines	S1 - Does the placement of dredged sediment at in-Bay disposal sites help with shores and wetlands?		✔	
	S2 - Can we develop sediment budgets for subembayments, tributaries, and the flux between the Golden Gate and outer coast?	✔		
	S3 - What is the sand budget of the Bay? What is the source and transport of sand moving on and off of Bay beaches?	✔		
	S4 - How would deeper water (due to sea-level rise) affect sediment deposition dynamics of mudflats and shallow subtidal shoals?	✔		
WRMP Management Questions				
How are external drivers (sea-level rise, development, changes in runoff/sediment supply) impacting tidal wetlands?	2A - How are the elevations of tidal marshes and tidal flats, including restoration projects, changing relative to local tidal datums?		✔	
	2B - What are the regional differences in the sources and amounts of sediment available to support the accretion and tidal marshes and adjacent habitats?	✔		✔
What information do we need to better understand regional lessons from tidal wetland restoration projects in the future?	4A - Where/when can interventions, such as placement of dredged material, reconnection to watershed sediment supplies, and construction of living shorelines, help sustain or increase tidal marshes + flats?	✔	✔	✔

3. Sediment Knowledge, Data Gaps and Needs

3.1 Bay Physiography and Sediment Dynamics

San Francisco Bay is classified as a tectonic estuary and occupies a tectonically active structural trough that formed during the late Cenozoic bordered by the Hayward Fault Zone to the east and the San Andreas Fault Zones to the west. The basin that formed in this trough has been occupied by an estuary during interglacial periods, but traversed by a fluvial system during glacial periods. The basin was most recently flooded during the Early Holocene between 10 ka and 11 ka, as rising sea level inundated the Sacramento River channel that cut through San Francisco Bay and the Golden Gate strait, and across the continental shelf 32 km at the glacial lowstand. It appears that the modern estuary was established by 7.7 ka, and by about 4 ka, the fringing marshes were established and conditions that are similar to the modern, partially-mixed estuary had emerged despite continuing oscillations between warm/dry and cool/wet conditions since that time (See reviews in Barnard et al., 2013a; b).

The physiography of the present Bay is very well described (for example see reviews in McKee et al., 2003; McKee et al., 2011; Barnard et al., 2013b). The Bay downstream from Mallard Island has an open water surface area of 460 mi^2 (~1200 km^2) at mean sea level (MSL) with a maximum depth of 143 m (469 ft) below MSL under the Golden Gate Bridge, and an average depth across the estuary of 7 m (23 ft) combining to a total MSL volume of 8.4 km^3. Tides are mixed semidiurnal with a tidal amplitude (mean high water to mean low water) at San Francisco near the Golden Gate Bridge (National Oceanographic and Atmospheric Administration (NOAA) station 18649 established 1854) of 1.25 m (4.1 feet). The latest information from NOAA shows that MSL presently is rising at a mean rate of 2.01 ± 0.21 mm (0.08 ± 0.008 in) per year.

On an annual average basis, the Bay receives about 25 km^3 of surface runoff from the Central Valley, about 1.6 km^3 of surface runoff and 0.2 km^3 of groundwater from local tributaries draining from the nine counties that surround the Bay, about 0.8 km^3 from discharges of treated wastewater, and about 0.4 km^3 from rainfall directly to the Bay surface (McKee et al., 2011). However the portion of each varies with season and location. The North San Francisco Bay is overwhelmingly dominated by river inflows and runoff throughout the year while in the South Bay, sewage treatment plant effluent is particularly important in the summer and evaporative losses can result in net water loss from the South Bay during summer periods (McKee et al., 2003; 2011). Water temperatures range from 46-50°F (8-10°C) in the winter to 68-77°F (20-25°C) in the summer; however, temperatures at the Golden Gate are warmer in the winter than in the South or North Bays and the reverse is true in the summer months, setting up density gradients which help to drive water fluxes and sediment dynamics (see reviews in McKee et al., 2011; Barnard et al., 2013).

Sediment supply to the Bay has also been well studied (for reviews see McKee et al., 2003; Barnard et al., 2013; Schoellhamer et al., 2018). Historically, pre-gold rush, it is estimated that the Central Valley supplied about 1.3 Mt/y whereas the local tributaries of the nine counties were estimated to supply about 0.8 Mt/y for the period 1909-66 (reviewed by Barnard et al., 2013). Historic supply was estimated to include about 50% sand-sized sediment from the Central Valley and bedload was about 8% of local tributary supply with an additional amount supplied as suspended sand (see reviews by McKee et al., 2003; Barnard et al., 2013). Due to the passing of the hydraulic mining debris, and extensive modifications to the drainages of the Central Valley, Delta, and local tributaries (dams, urban and agricultural development, channelization and dredging), supply has diminished from the Central Valley sources and Bay sediment inputs are now dominated by local small tributaries (1.4 Mt/y; 60%) with just 0.9 Mt/y from the Central Valley (McKee et al., 2013). However, the estimates of relative supply for each year can vary from 81% supply from small tributaries to 65% supply from Central Valley Rivers (McKee et al., 2013) and the overall annual average is a function of the averaging period (Schoellhamer et al., 2018). Presently, sediment removal by dredging is equivalent to the estimated supply of sand to the Bay such that net sand flux is estimated to be zero under the current management and policy regime (Schoellhamer et al., 2018).

The physics of Bay sediment dynamics has been studied and the Bay has been monitored and modeled for decades (e.g., the compilations of Conomos, 1979; Hollibaugh, 1996; Barnard et al., 2013a, b). Since 2013, the USGS, universities, private consultants, non-profit research institutions, other RMP workgroups, and BCDC have carried out numerous additional studies (many cited in later sections of this strategy document). In addition, at least one sediment planning document has been completed for Central San Francisco Bay (BCDC, 2016b), and there are several other sediment planning documents being developed concurrently by BCDC and the WRMP with complementary foci to the RMP. Based on all this work, it appears that San Francisco Bay is one of the more complex systems in the world due to its:

1. climatic location (subject to “tropical atmospheric rivers” from the south and polar derived cold fronts from the north),
2. geographic position within the San Andreas fault zone,
3. receipt of runoff and sediment loads from two spatially and temporally separated sources: snowmelt runoff from the Sierra Nevada Mountains and rainfall runoff from the coastal range,
4. urban history spanning 150 years including the use of Bay for commuter transportation, recreational sailing, and as a major rail and shipping hub leading to channel deepening, and
5. large scale modification of the shoreline to support urban growth, waste disposal, salt extraction, and agriculture leading to the infilling of about a third of the surface extent.

The first three of these drivers of complexity lead to a system that is highly dichotomous; quiescent much of the time and then “awakened” by stochastic events that cause large changes in the water and sediment budgets in very short periods of time. Although not often conceived in the initial phases of monitoring, long time-series data are necessary in such a system to describe general character and can be used to identify trends and step changes, tease out causative forcing factors, and usually capture rare stochastic events that may be highly influential on system processes. Long-term, continuous monitoring is also important because the value of data invariably increases with time.

The last two drivers provide a complex anthropogenic framework within which the natural processes are further modified. Therefore, although we think of the Bay as a single place, in reality it is a system of estuaries with hundreds of river and creek mouths with unique morphology, time-varying freshwater supplies, salinity gradients, turbidity maxima, biologies, and human infrastructure. Thus, the magnitude and direction of sediment transport around the Bay changes across tidal, seasonal, and decadal timescales, and differs geographically between subembayments and how the sediment transport processes interact with Bay biology and all the human factors.

With all this complexity, monitoring sediment processes within the Bay is a difficult enterprise that must aim to subsample a very wide variety of temporally and spatially varying processes, and be carried out across the watershed and the Bay and over sustained time periods. Models need to be supported by appropriate data in relation to the management questions being answered. Given all this complexity, the models of the Bay developed to-date have been data limited but are gradually evolving in sophistication as data evolves and computing power and other runtime limitations have been revolved. Ultimately, we aim to get to a point where the models and data collection efforts synergistically interact, one informing the other. But how do we decide what to do next given all this complexity? In the next sections we will outline a basic conceptual model for San Francisco Bay as a framework for further decision around resource allocations in relation to the monitoring and modeling recommendations that are summarized in later sections.

3.2 A High Level Bay Sediment Conceptual Model

As scientists study sediment processes in estuaries, they tend to go through a series of steps:

1. Describing the basic geography and physics (watershed area, surface area, water depth, tides, bathymetry, habitat types, salinity, temperature, suspended sediment concentrations),
2. Estimating system and subsystem water, salt, and sediment budgets, and
3. Describing vertical and horizontal sediment concentration and flux gradients often in relation to management or policy drivers or intellectual curiosity (universities and students).

Although these are the major three steps, in reality some steps can be done in parallel and they can be done out of order, but when this happens, scientists and managers often find themselves circling back to ensure there is agreement on the system basics within which to frame more complex temporal and spatial processes.

So where are we in this hierarchical system of knowledge? As described above, we have considerable and sufficient knowledge on the Bay physiography. We have a partial but incomplete whole system sediment budget for fine sediments (<0.0625 mm) (Schoellhamer et al., 2005) and lesser reliability on sand sized sediment (Perry et al., 2015), and we have partially resolved subsystem fine sediment budgets for the Bay between Mallard Island and the Benicia bridge and for the Bay south of Dumbarton Bridge (Schoellhamer et al., 2018). Discussed in detail in subsequent sections, we have few measurements for concentrations and fluxes between the bed and the water column (erosion and resuspension processes), and we have few measurements of movement of sediments from the deeper channels onto subtidal shoals, mudflats, and into and out of sloughs, wetlands, and tidal flood control channels (especially given the complexity of the Bay).

Strategic recommendations for Bay sediment monitoring and modeling efforts need to address the most pressing data gaps in our current knowledge. The most important gaps to resolve are those that concern high-magnitude sediment pathways, loadings, sinks, and sources, and those with the greatest amount of uncertainty. In order to communicate the strengths and weaknesses of currently available information, conceptual models can be used as a framework to present known and missing information and uncertainties. Usually, the various concepts and the process of sediment science are explained diagrammatically. As indicated above, there are at least four conceptual models that can be developed for the Bay. Whole system (1) and subsystem sediment budgets (2), vertical sediment processes within the water column (3), and horizontal sediment transport to and from deeper and shallower areas (4). For this strategy, we present a single holistic whole system conceptual model to help focus us on decisions to support improvement monitoring and modeling needs. This holistic model will be built upon in a subsequent RMP SedWG supplemental environmental project (SEP), scheduled for completion in 2021.

3.2.1 Whole system conceptual model

The whole system conceptual model is generated from considering all the main pathways of sediment supply, storage, and loss (Figure 1). Here we define the Bay boundaries to be Mallard Island on the Sacramento River just upstream from Suisun Bay, the head of tide on all the smaller tributary mouths that feed into the Bay from the nine counties that surround the Bay, the extent of tides on the Bay margin and within the wetlands that fringe the Bay, the Golden Gate Bridge that spans the Golden Gate Strait, and the bed of the Bay. In this simple conceptual model, the roles of subsidence and tectonic uplift are not considered and the supplies of sediment via atmospheric deposition and treated wastewater are included but known to be minor. The main pathways and boundaries in this model are:

- External sediment loadings to San Francisco Bay
    - Tributary sediment supply (from the Bay Area nine adjacent counties)
    - Delta sediment supply (Central Valley Sacramento and San Joaquin large rivers)
    - Municipal and Industrial wastewater load (~24,000 t/year - not considered further)
    - Bay surface atmospheric deposition (~12,000 t/year - not considered further)

- Sediment sinks and reservoirs in the Bay
    - Change in bathymetry (erosion and deposition through entrainment and wind/wave resuspension)
    - Sand Mining (removal of sediment mainly for use in construction)
    - Navigational dredging (disposal to the ocean or semi-permanent storage in wetland restoration sites)
- Pathways of sediment transport
    - Flux through the Golden Gate to and from the nearshore outer coast
    - Flux between subembayments (not illustrated on the conceptual model)
    - Flux within subembayments
        - Margin tidal and deeper Bay tidal channels
        - Across mudflats and shoals
        - Into and out of wetlands

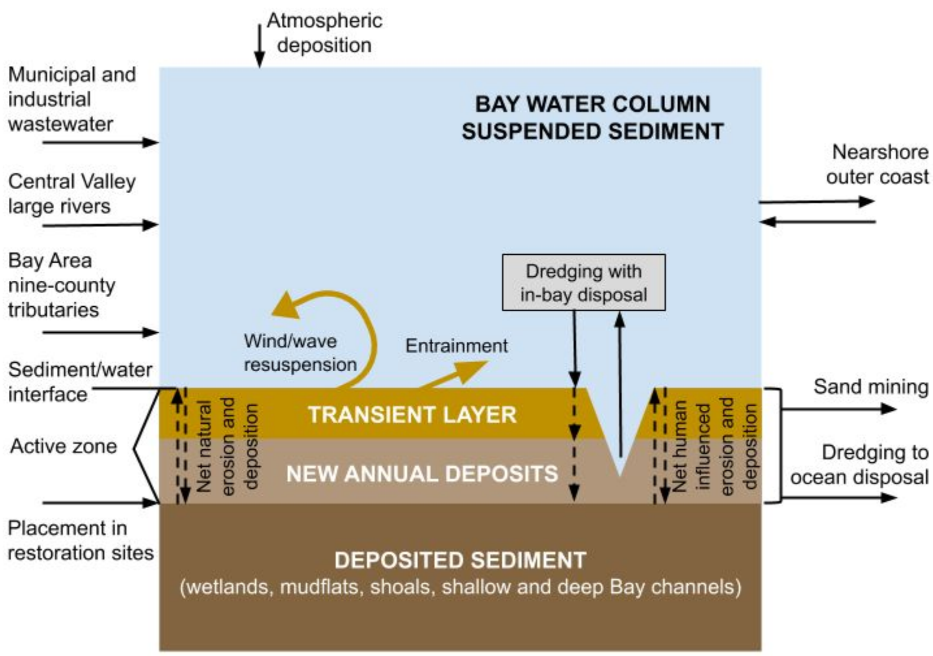

Figure 1. Whole system mass balance conceptual model (modified from Krone, 1979).

In addition to these fluxes, there are important sediment and water column properties that need to be continually described and recorded in databases for the Bay Area sediment community to access in order to develop models and describe system transport processes:

- Sediment characteristics
    - Grain size

    - Organic matter content
    - Bathymetric texture and biology
    - Cohesiveness, thresholds for critical shear stress for resuspension and movement
- Water column characteristics
    - Turbidity patterns and suspended sediment concentrations
    - Flocculation

Below we describe the data gaps in our current state of knowledge on sediment processes within the Bay. Important data gaps and current conceptual understandings are presented in the context of the RMP Sediment Management Questions, introduced in section 2. Current data gaps and subsequent monitoring and modeling recommendations all fall within the scope of management questions 3-5, which encompass process on sediment sources, loadings, pathways, and sinks; passive sedimentation of marshes and restoration sites; sediment characteristics; and water column characterizations concerning SSC and proxy measurements. Subsections 3.3, 3.4 and 3.5 delineate these three management questions, and the subsections within each of those describe different data gap components for each management question.

3.3 Data gaps and needs associated with Management Question 3: What are the sources, sinks, pathways, and loadings of sediment and sediment-bound contaminants to and within the Bay and subembayments?

3.3.1 External sediment loadings to San Francisco Bay

Tributary sediment supply

Regional-scale sediment loads from ungaged small tributaries have to be inferred from data in representative watersheds using simple algebra and regression statistics (e.g., McKee et al., 2013). The development and use of a dynamic simulation model would improve the efficiency of future estimates for ungauged streams, estimating storage in flood control channels, and for simulating changes in hydrology and sediment load due to the implementation of best management practices, land-use change, land and water management, and climate change. The development of such a model would need to be supported by an observational network.

Given the microclimates within the Bay Area, it is important to have a network of monitoring stations that are spatially distributed; several in each county on the larger tributaries would be a good starting point for consideration. Data collection that is presently operating should be continued if understanding trends in relation to climate and land-use change is a high priority, and if understanding the potential for large storms to trigger mass-wasting processes such as landslides, debris flows, and mudflows and associated multi-year effects on sediment loads is a high priority. The overall goal is to maintain the existing long-term gauging sites and add new gages in watersheds that supply a large fraction of sediment in different subembayments by reoccupying historic gauging sites to extend time series. To review the detailed arguments for recommended tributary sediment monitoring, the reader is referred to Schoellhamer et al. (2018). The main existing sites are:

- Alameda Creek at Niles (suspended and bedload)
- San Lorenzo Creek at San Lorenzo (suspended load)
- Guadalupe River above Highway 101 at San Jose (suspended load)

Some recently added sites include:

- Belmont Creek (Planned for WY 2021),
- Arroyo Corte Madera del Presidio (WY 2020 and planned for WY 2021),
- Novato Creek at Novato (WY 2020 and planned for WY 2021), and
- Walnut Creek (Planned for WY 2021)

With the exception of Alameda Creek at Niles, these monitoring sites lack bedload data, which is important for resolving the sand budget for the Bay. Developing a relationship between bedload and suspended sediment at these sites would be informative for modeling fluxes at other large Bay tributaries. There are, however, important differences between Bay tributaries, including differing geological terrains, precipitation gradients, and microclimates. The range of these differences is not currently captured by the monitored sites listed above. The inclusion of tributaries draining all geographic regions of the Bay would help inform models of unmonitored areas.

In summary, our general recommendation is to carry out a minimum of three years of suspended sediment and bedload monitoring at two key large tributaries in each of the fringing counties of the Bay. Because rare events transport large masses of sediment that strongly influence long-term averages (e.g., McKee et al., 2013; 2017; East et al., 2018), if a 1:5 year return storm event is not captured during the first three years of monitoring, additional years should be funded. The recently added sites will only be monitored for one or two years due to funding limitations; depending on the data, a continuation of these sites for additional years will likely be recommended. Developing a watershed sediment loading model and planning an observation network that is mainly focused on trace contaminants are already funded in 2020 and 2021 by the RMP SPLWG, but decisions about funding the sediment loads network should be coordinated between the SMMS and the SPLWG. Our key recommendations for tributaries are included in a later section of this document.

Delta sediment supply

Suspended sediment supply from the Sacramento and San Joaquin Rivers above the head of the tide is very well quantified (Wright and Schoellhamer, 2004) and those measurements should continue but are likely outside the purview of the RMP. The Delta traps suspended sediment so the supply to the Bay is about 33% of the supply to the Delta (Wright and Schoellhamer, 2005). Suspended sediment supply to the Bay as defined by the RMP has been quantified at Mallard Island (McKee et al., 2013; Schoellhamer et al., 2018) and is the largest single terrestrial supply in the Bay’s mass balance. The method for estimating suspended sediment load from SSC is well established (McKee et al., 2002; 2006), but it is based on detailed data collected in the 1990s prior to the 1999 step decrease in SSC (Schoellhamer, 2011). It is possible that the regression-based formulas used to convert the continuous surrogate proxy measurement of turbidity at the edge of the main channel just off Mallard Island to bidirectional flux in the whole cross-section are no longer accurate. For example, with lower advective flux, the vertical and horizontal variation in the water column may have changed. In addition, given recent restoration of some Delta Islands and generally lower suspended sediment concentrations in the water column of San Francisco Bay, the redistribution of sediment during the dry season may have shifted in favor of either the Delta (due to restoration) or the Bay due to concentration gradients. Measurements are needed to ascertain the nature of any changes. Given the Delta is the largest single supply to San Francisco Bay, errors in our loading estimate from this source may have an undesirable influence on our understanding of the net Bay sediment budget.

Bedload measurements in the vicinity of Mallard Island would help resolve the effect of sand mining and dredging on bedload supply to the Bay. The likely bounds of coarse sediment at Mallard Island are estimated by calculating bedload at gauging stations 25 km upstream and assuming that either that rate does not change or that sediment removal from the intervening reach is replenished by bedload. Both assumptions are significant and unproven. Collection of water velocity data at Mallard Island during a series of 24-hour deployments covering spring, neap tides, and a few winter high flow events in coordination with detailed tidal measurements of bed-material size, and bedload in the cross-section would likely provide an improved method for estimating the supply of bedload to San Francisco Bay at Mallard Island. Alternatively, acoustic measurements of bedforms and motion of bedforms could be used for estimating bedload (Dinehart, 2002). Another approach would be to calibrate a multi-dimensional numerical model of hydrodynamics and bedload transport such that it could consider cross-sectional variability when calculating bedload. There would likely be an overlap in the data needed to improve the reliability of estimates of suspended and bedload at Mallard Island. Although coarse sediment supply is relatively small compared to fine sediment supply, coarse sediment has higher importance in the context of sea-level rise challenges, beach nourishment, wave energy dispersion, and the future of sand mining in the Bay.

In summary, the main data gaps for the input of sediment from the large rivers and Delta are uncertainties about the accuracy and validity of the proxy method developed by McKee et al. (2006) and the lack of robust bedload measurements. Our recommendations at the end of the strategy reflect these weaknesses.

3.3.2 Pathways of sediment transport

Flux through the Golden Gate

Whether the nearshore coastal ocean, connected to the Bay by the Golden Gate, is a net sink or a net source of sand (0.0625-2 mm) and fine silts and clays (< 0.0625 mm) to the Bay remains an open question. This is due to the sparse number of studies, the complexity of processes, the fact that net residual flux is small compared to the instantaneous peak flux, and logistical challenges (strong winds, tides, and wave energy) that obstruct the expansion of observations beyond short snapshots of time. Although the majority of research done to date does suggest net seaward flux of fine (Barnard et al., 2013b) and coarse sediment (Barnard et al., 2013c), recent work by Downing-Kunz et al. (2017; in review) counterintuitively reported net landward flux of fine sediment during the falling stage of high delta outflow conditions, thus elucidating complexities that require further observations and modeling to resolve. Given sand supply has been largely cut off from the watersheds (Schoellhamer et al., 2018), it is very important to better quantify the direction (Barnard et al., 2013c) and magnitude of sand flux at the Golden Gate to describe the net sand budget for the Bay. At this time there is no estimate of net bedload (sand) sediment flux.

A combination of modeling and measurements can be used to develop surrogate relationships for sediment transport at the Golden Gate, similar to those used at Mallard Island and Benicia Bridge, enabling the long-term collection of the less costly surrogate data to estimate fluxes at timescales useful for management. Downing-Kunz et al. (2017) attempted to apply the surrogate sediment flux equation presented in Erikson et al. (2013) but discovered some methodological problems and indications that the equation is not applicable to flows greater than 1450 m^3/s. Due to correlations for SSC, water, and sediment flux between the Golden Gate and Alcatraz, Downing-Kunz et al. (2017) still concluded that the turbidity sensor mounted near Alcatraz Island was a potentially good surrogate for Golden Gate flux if a better reference velocity could be established. However, there may be challenges when Central Bay is fresh and stratified likely due to the mid-depth mounting of the sensor (might need two sensors or a different mounting depth). It might be possible to use a numerical model to identify a better depth or location for a proxy sensor. In 2020 the SedWG funded a modeling study to simulate the sediment flux across the February 2017 high flow period, validate the model-predicted sediment flux using the one tidal cycle of flux observations collected by Downing-Kunz et al. (2017), and compute the total predicted sediment flux through the Golden Gate over a 3-month period. Results are expected in early 2021. This study, while a step forward, is unlikely to result in the development of a robust proxy for mass flux estimation, nor is it intended to make any estimates of bedload transport. BCDC and the State Coastal Conservancy issued a request for proposals and qualification (RFPQ) entitled “Fall 2020 Research to Understand Impacts of Bay Sand Mining on Sand Supply and Transport in San Francisco Bay and Outer Coast.” Modeling done in response to this RFPQ may provide some further insight into both the direction and magnitude of sand transport through the Golden Gate cross section during 2021 and 2022.

In summary, suspended sediment flux through the Golden Gate is poorly characterized due to logistics and the lack of verified surrogate measures to extend the estimates beyond the timescales of empirical measurements. Further field measurement during winter storms coupled with further numerical modeling could be used to estimate long-term suspended sediment fluxes. Recommendations for bedload sediment cannot be made at this time but are expected in 2021 and 2022 based on the work done in response to the BCDC/SCC sand sediment science RFPQ.

Flux between subembayments

San Francisco Bay can be conceptualized as a series of connected subembayments that differ in terms of terrestrial sediment supply, freshwater inflow, salinity, bathymetry, and ocean connectivity. The boundaries of some of these subembayments are defined by constrictions in geometry (e.g., Carquinez Strait, Richmond San Rafael Bridge), while others are defined by the availability of bridges for deployment of instruments (e.g., San Mateo Bridge). Suspended sediment transport between subembayments is difficult to estimate because of large cross-sections and tides that produce high spatial and temporal variability of sediment in the water column and saltation and rolling along the bed. To date, empirical estimates have been made at Dumbarton (Shellenbarger et al., 2013; Livsey et al., 2019) and Benicia Bridges (Ganju and Schoellhamer, 2006; Schoellhamer et al., 2018). However, it was discovered that flocculation in the Dumbarton cross-section is causing inaccuracies in the flux estimates. Livsey et al. (2019; 2020a; 2020b) have developed a correction factor for tidal asymmetry in relation to the size of suspended flocs. This correction can be used to adjust the relationship between turbidity and suspended sediment concentration to compute a more accurate estimate of annual flux. More recent work funded by a SEP overseen by the RMP is now also calling into question the magnitude and direction of flux at the Benicia Bridge due to flocculation processes and secondary flow circulation and two countervailing cells (Livsey, personal communication, September 2020). Thus for reasons unique to each cross-section, the fluxes so far computed from empirical field measurements at both Dumbarton and Benicia Bridges are now being reconsidered.

Another weakness in the Dumbarton data set is the lack of information collected during a period of large discharge from either South Bay small tributaries or the Delta. Thus, concerns remain that proxy measures such as flow or continuous measures of SSC may not be extensible for estimating flux for wet years. At present, the USGS has no ongoing flux data collection in 2020; flux estimates for Dumbarton Bridge from calendar years 2018-2019 were provided to the RMP in spring 2020, but no flux monitoring is currently funded in 2020 and no data were collected during the very wet winter of January-April 2017. This may also be a concern for other cross-sections. In addition, loads estimates for the Benicia Bridge (Schoellhamer et al., 2018) used surrogate relationships dependent on Delta outflow and measured SSC to estimate long-term flux based on data collected 15 years ago (but after the step change (Schoellhamer, 2011)). This may require further checking. Thus, at this time, there are no decadal-scale estimates of flux for any cross-section that are fully verified for high-flow conditions when major morphological changes can take place, yet this is very important information in the context the sediment demands associated with 50-year restoration plans in Lower South Bay, but also more generally.

The above subembayment-scale sediment flux monitoring and modeling efforts have been focused on total suspended sediment fluxes and do not estimate the flux of sand in suspension or transported along the bed as bedload. This is an important limitation on current understanding of sand transport in the Estuary. To understand and estimate fluxes of sand in the Estuary, measurements of sand transported in suspension and bedload are needed. Percent sand analyses from suspended sediment samples collected by the USGS indicate the sand content in samples from Central, San Pablo Bay, and Suisun Bay can be as high as 25%. Suspended sediment monitoring efforts could include increased measurements of percent sand, as well as instrumentation to continuously estimate percent sand in suspension. These data could be used to validate sediment transport models used to estimate sand fluxes in the Estuary. Bedload monitoring or flux estimates using other methods at key cross-sections (e.g., Dumbarton, Benicia Bridge, Richmond/San Rafael Bridge) would provide data to calibrate and validate models that aim to estimate and predict interannual fluxes of sand in the Estuary.

To predict subembayment-scale suspended sediment fluxes throughout the Estuary, an integration of short-term field campaigns, long-term monitoring, and numerical modeling is needed. Previous studies of suspended sediment flux have coupled short-term field campaigns to collect high-resolution flow and sediment data at a cross-section with long-term monitoring of suspended sediment by the USGS to estimate interannual sediment fluxes (e.g., Ganju and Schoellhamer, 2006; Schoellhamer et al., 2018). Recent efforts funded by the RMP in cooperation with Anchor QEA have focused on integrating numerical models of sediment transport with field-based measurements at the GG to both improve the model and extend the time scale of the field observations from the daily time-scale to weeks and months.

Sediment transport models can estimate fluxes throughout the Estuary and provide predictions of future changes in sediment supply, but must be employed in concert with relevant field observations for model validation. For example, recent measurements at Dumbarton Bridge have highlighted the need to include flocculation (i.e., aggregation and break-up) of suspended silts and clays, a process not included in current sediment transport models of the Estuary (Amoudry and Souza, 2011). Flocculation, when included in sediment-flux measurements at Dumbarton Bridge, reversed the sign of previously-published sediment flux measurements for Lower South Bay from net seaward to net landward from 2009 to 2011 and 2013 to 2016 (Livsey et al., 2019). Because processes that control flocculation vary in the Estuary (Manning and Schoellhamer, 2013; Huang, 2017), spatially distributed measurements of flocculation and sediment flux are needed to calibrate and validate sediment transport models that aim to generalize suspended sediment flux measurements.

In summary, sediment flux measurements have been made at two key estuary boundaries: the downstream boundary of Suisun Bay (Benicia Bridge) and the downstream boundary of Lower South Bay (Dumbarton Bridge). At each of these locations, there are concerns about previous data interpretations that did not include key processes (flocculation, secondary cell circulation) and the lack of data during recent large storm events. There is no such data available for the Richmond-San Rafael bridge cross-section. Further measurements of fluxes at key cross-sections have been identified as key data needed for Bay modeling (RMP SedWG Modeling Workshop, October 2019). Measurements of flocculation and suspended sediment flux (in-situ measurements of velocity and turbidity/SSC coupled with boat-based cross-section analysis over selected tidal cycles) should be integrated with sediment transport models at key cross-sections within the Estuary. The estuary is currently devoid of bedload measurements, but these could be done at key cross-sections.

Flux within subembayments

In margin tidal channels

San Francisco Bay was historically surrounded by hundreds of thousands of acres of tidal marshes that were etched with an intricate series of tidal sloughs. From the earliest times of European settlement, selected sloughs nearer to the permanent river and creek mouths were modified for navigation to provide a link between the bounties of forest and farmland and the growing cities of Oakland, San Francisco, and San Jose (SFEI-ASC, 2016). Over the last 120 years, many of the slough systems were permanently leveed to support flood control, while tide gates have muted the tidal process in many others. Awareness of sediment flux and deposition in slough and channel systems has grown since the 1960s and 1970s when flood control channels began to require regular maintenance dredging. Sediment has been removed from the tidal reaches of 23 flood control channels on the Bay margin to maintain conveyance capacity, but with impacts to habitats. For the period 2000-2013, 1.2 million cubic yards of sediment was removed with > 60% disposed of as waste at an average cost of $700,000 per square mile dredged (SFEI-ASC, 2016). Reliable sediment budgets based on loads, net deposition, and removal data for flood control channels are only available for a few channels. In Walnut and San Francisquito Creeks, an estimated 14% and 11% of the fluvial input to the head of the channel is either stored or removed during maintenance. In the case of Walnut Creek, 993,530 cubic yards of sediment was removed from the tidal section of the flood channel from 1965-2007, most of which was likely sourced from the Bay but some or perhaps significant amounts came from the watershed (Downing-Kunz and Schoellhamer, 2015). In the case of Alameda Creek, 26% of the net sediment supply from the watershed is permanently being stored in the fluvial portions of the flood channel and an average of 34% is removed by maintenance activities. Grain size data indicate net storage and removal of coarser materials, leaving only the fine portion and just 40% of the total mass getting to the tidal channel and out to the Bay. In a similar fashion to Walnut Creek, a total of 264,814 cubic yards of sediment were removed from the tidal section of the Alameda flood channel from 1975-2013 (SFEI-ASC, 2016).

Given the habitat impacts, disposal, and cost challenges, a series of more detailed studies have been completed looking at the dynamics of tidal channel processes on the Bay margin. Where these detailed studies coincide with flood management questions, they provide excellent datasets to control the boundary conditions of models designed to support channel management and decisions about restoration and reconnection of channels to local Baylands. The first of these studies was conducted in the Napa-Sonoma Baylands and Mare Island Strait (Warner et al., 1999; 2002; 2003; 2006). Warner et al. (2002; 2006) described a local low salinity convergence zone associated with the landward and seaward baroclinic pressure gradients in Mare Island Strait where local sedimentation rates were enhanced. Warner et al. (2003) explored similar processes in the tidal sloughs that pass between the Napa and Sonoma systems within the wetland complex. Their data showed how the asymmetry of east and west tides meet to produce a barotropic convergence zone that controls the transport of water and sediment. During spring tides, tidally averaged water-surface elevations were higher on the truncated west side creating tidally averaged fluxes of water and sediment to the east, whereas the opposite occurs on neap tides (see Warner et al., 1999 for the raw velocity, stage, turbidity, and SSC data).

These concepts were further developed by Ganju et al. (2004), who deployed instruments to measure stage, turbidity, and SSC in the mouth of the Petaluma River and in the Napa number 2 slough near the confluence with Sonoma Creek. They described the existence of an oscillating deposit of sediment that moved up- or down-stream associated with the varying position of the turbidity maximum and served as a mediator between the sediment supply from rivers to the Bay. Ralston and Stacy (2007) studied the tidal and meteorological forcing of sediment transport in tributary mudflat channels (Meeker Slough) near Richmond. They found that suspended sediment transport was controlled by advection and dispersion of a tidal salinity front and that during calm weather when tidal forcing was dominant, high concentrations of suspended sediment advected up the mudflat channel. Net transport in the tributary channel was generally offshore during storms and during calm weather spring tides, and onshore during calm weather neap tides.

Building upon this, moored acoustic and optical instruments were deployed near the mouth of Corte Madera Creek to explore suspended sediment dynamics (Downing-Kunz and Schoellhamer, 2013). They found that during wet periods, net suspended sediment flux was advective and seaward and associated with high turbidity ebb tides whereas, during dry periods, net flux was dispersive and landward and associated with flood tides when high turbidity was caused by either wind-wave resuspension (summer months) or high flood velocity (autumn months) leading to local resuspension. A few relatively large events were found to dominate fluxes; estuary mouths where these processes occur may be net sinks for sediment and thus tributary supply may be an overestimate of flux to the wider estuary (Downing-Kunz and Schoellhamer, 2013). In their follow-on paper, they quantified the trapping efficiency of the tidal reach by comparing accumulated mass from the upstream gage with accumulated net flux in the mouth of the tidal reach. They found that during dry periods and small storms there was net trapping, but it was diminished with increasing storm size and in some instances, net erosion of previously-stored sediment occurred (Downing-Kunz and Schoellhamer, 2015), similar to observations in the Brisbane River Estuary (Eyre et al., 1998) and Richmond River Estuary (Hossain and Eyre, 2002) in Australia. However, overall, during three water years, 50% of the advected sediment from the watershed was stored in the tidal reach indicating that sediment estimates from upstream gauging may overestimate the sediment supply to the open waters of the Bay beyond tributary mouths (Downing-Kunz and Schoellhamer, 2015). This also suggests that a large portion of sediment that is removed from the tidal reaches of flood control channels around the Bay may in fact be from the upstream watershed (see the previous section).

Alviso Slough in South Bay has also been the subject of detailed studies (Shellenbarger et al., 2015; Foxgrover et al., 2019). Shellenbarger et al. (2015) deployed continuously measuring sensors for temperature, salinity, depth, turbidity, and velocity in 2010 in Alviso Slough. They found that, in WY 2010, an average year, extreme events landward (salt wedge) and bayward (rainfall events) account for 5% of the total sediment flux in the slough and during only 0.55% of the time, with the remaining 95% of the total sediment flux due to tidal transport causing net landward flux. These results corroborated the Corte Madera results and imply that sediment in the sloughs from watershed sources may not be flushed to the Bay and are not available for sedimentation in the adjacent marshes and ponds (Shellenbarger et al., 2015). Foxgrover et al. (2019) used high-resolution biannual measurements of bathymetry over the period WY 2011-2017 to estimate net bathymetric change. They observed seasonal variability and a general pattern of higher volumes of net erosion during the winter months and either decreased amounts of erosion or net sedimentation over the spring and summer months with overall average net deposition during non-winter months. Out of the first six winter seasons surveyed, all except the 2016 winter had a net erosion of sediment and WY 2017 (a very wet year) experienced the greatest net erosion in the slough (Foxgrover et al., 2019). Their results generally corroborated those of Shellenbarger et al. (2015), concluding that sediment scour occurs over winter months as a result of increased watershed discharge but that increased tidal current velocities due to levee breaches and A8-TCS gate operations also played a role along with larger Bay scale circulation patterns. Their results of overall net erosion during the seven years does appear to contrast with the results of Downing-Kunz and Schoellhamer (2015) for the tidal mouth of Corte Madera Creek and the results of Shellenbarger et al. (2015) for Alviso Slough for WY 2010, the year before the Foxgrover et al. (2019) study began, perhaps because of the sediment sink caused by the wetland restoration levee breaches.

In summary, much has been learned about sediment transport processes in the tidal portions of the mouths of some key tributaries. Net sedimentation occurs in non-wet season months of the tidal reaches of all tributaries so far surveyed with the exception of Alviso where temporary erosion may be taking place due to salt pond levee breaches (Foxgrover et al., 2019). It appears that a large portion of upstream derived watershed sediment is trapped and that, overall, the Bay sediment budget is mediated by dispersive tidal forces occurring in tidal channels just downstream from the fresh-saltwater interface. Although it is clear that these interfaces switch between net erosional and depositional depending on the season and storm forcing for individual years, so far, no long term study has been completed to determine if the net of advective sediment supply and tidal dispersive forces results in a net permanent sediment trap at decadal time scales. But it is reasonable to hypothesize that net trapping of coarse sediment is more likely in both the fluvial and tidal portions of these channels. It remains unclear whether during sea-level rise (transgression) the net permanent deposition could occur due to a steeping (shortening) salinity transition zone, or if the increased storminess and likely increased watershed flow and sediment supply (Dusterhoff and McKnight, 2020) would cause greater net erosion and transmission to the wider Bay.

With the wealth of tidal studies available, recommendations reflect the lack of long term studies, the lack of attention to coarse sediment, and the general lack of sufficient local data to support the calibration of modeling-based planning for wetland restoration in all margins of the Bay. The October 2019 RMP SedWG Modeling Workshop recommended the collection of more flux data in key cross-sections. To support model calibrations, studies in locations of key flood control and wetland restoration activities, particularly in South Bay (Alameda Creek for example), western San Pablo Bay (Novato Creek for example), Napa and Sonoma, and along the Contra Costa County coastline (Walnut Creek for example).

On the subtidal shoals

Sediment-flux modeling and data are mostly concentrated along the main-channel of the Bay and are more limited on the broad subtidal shoals, which are found in many areas of San Francisco Bay. This is problematic because near-shore, cross-shoal fluxes are relevant to coastal resiliency and restoration efforts along Bay shorelines and can directly nourish marsh plains (Lacy et al., 2020). However many isolated studies have been completed and appear to have begun with the work of Sternberg et al. (1986) who monitored flow conditions and suspended sediment distribution of a tidal channel on the edge of Southampton Shoal east of Tiburon Peninsula every 15 minutes over six successive flood and ebb-tidal cycles and computed fluxes in the vertical profile. The highest fluxes occurred near the bed associated with the highest SSC.

Since then, a wealth of studies have emerged (Kranck and Milligan, 1992; Schoellhamer, 1996; Lacy et al., 1996; 2003; Talke and Stacey, 2008; Brand et al., 2010). From these works, a series of general concepts have emerged. Resuspension in the Bay is driven by tidal currents in the deeper channels and predominantly by wind waves in the shallows. Sediment is redistributed around the Bay by local wind waves generated over the extensive shallows and mudflats by strong, diurnal, summer winds (Schoellhamer, 1996; Talke and Stacey, 2008; Brand et al., 2010). Wind waves are more effective at resuspending sediment at low water each tide, so SSC in the shallows is generally higher during flood tides, particularly when persistent winds are present in the summer and fall. This dynamic can result in a net sediment flux determined by the direction of the flood tide (Lacy et al., 1996). Brand et al. (2010) showed that seasonal wave-induced resuspension is an important factor for overall sediment transport in shoal-channel estuaries, such as in the South Bay. Brand et al. (2010) noted that while wind waves are important for sediment resuspension on subtidal shoals, large increases in sediment flux throughout the Bay are due to the nonlinear interaction of both wind waves and tidal currents.

Given these concepts, the RMP has a wealth of spatially discrete SSC data, but the temporal dynamics of concentrations, the processes of erosion and deposition and fluxes on the subtidal shoals are isolated to a few locations and are generally lacking for a set of representative locations around the Bay. Notably, there are few long-term records of SSC in shallow areas. There are records of 6 to 10 weeks at various locations in San Pablo and South Bay, but continuous records are needed to determine long term trends to capture the influence of sea-level rise and changes in sediment supply. The October 2019 RMP SedWG Modeling Workshop identified continuous SSC monitoring in the shallows of each subembayment as a priority. If these data were coupled with velocity data and sediment profiles, flux profiles could also be generated. There is good information on the influence of waves and currents on SSC, as well as the influence of depth in San Pablo Bay. In the South Bay, north of the Dumbarton Bridge, there is a lack of data on the eastern edge of the eastern subtidal shoals. The eastern shoals north of the San Mateo Bridge represent another data gap. Although there are studies of fluxes on the subtidal shoals, there are few studies linking processes at broader scales, such as fluxes from the Bay axis to inter-shoal channels, across subtidal shoals and up onto the marsh plain. Concurrent monitoring of flocculation and fluxes along channel-shoal transects would allow investigation and model calibration across this important transition zone from the main channel to the shoreline (RMP SedWG Modeling Workshop). Concurrent channel-shoal monitoring is needed to determine how flocculation processes vary between the channel and subtidal shoal.

3.3.3 Sediment sinks and reservoirs in the Bay (change in bathymetry)

Sedimentation and erosion are occurring and constantly changing with season and location in the Bay. Conceptually, tidal creeks and channels on the margins, wetlands, mudflats, subtidal shoals, and deep channels and the broader Bay can all undergo cycles of erosion and deposition and when this is permanent at the timescales of management interest (perhaps 50-100 years for wetlands in the context of sea-level rise, or 50 years for a levee, flood control channel, bridge or road passing through the wetlands, or 20-30 years in the case of a private marina, or a few years in the case of shipping channels and ports), this results in the need for sediment management or structural redesign. When the results are net permanent deposition, this is called a net sediment sink. These processes are observed by bathymetric surveys and are carried out at appropriate time scales for each management need.

At a Bay-wide scale, the USGS has developed historic bathymetric digital elevation models (DEMs) of San Francisco Bay from surveys conducted by NOAA's Office of Coast Survey beginning in the 1850s and ending in the 1990s. Analysis of these DEMs shows historic patterns of sediment deposition and erosion. These results turned out to be invaluable for understanding pathways of sediment and sediment-bound contaminants within the Bay and subembayments, for closing sediment budgets, for supporting the PCB and Hg TMDLs, supporting decisions related to salt pond restoration, navigational dredging, and sand mining, among many other uses. However, given decreased sediment supply from the Delta over the past 60 years (Krone, 1996; Schoellhamer, 2011) and a corresponding increase in the relative importance of sediment supply from local tributaries (Krone, 1996; McKee et al., 2013), it seems likely that Bay bathymetry may have responded. Unfortunately, there is no comprehensive, Bay-wide documentation of the recent (25 to 35 years) of erosion and deposition on the Bay bottom. Recently, the Ocean Protection Council (OPC), NOAA, USGS, and California State University Monterey Bay carried out surveys of various portions of the Bay. With RMP funding from the SedWG, a new Bay DEM is being created that will allow a new change analysis to be completed (Fregoso et al., in preparation).

For any future analyses, a continuing data limitation will be accurate recent bathymetric data. This has recently been resolved by OPC, NOAA, USGS, and California State University Monterey Bay, but how often should Bay-wide surveys be repeated? The theoretical answer to this question varies from 2-5 years at the scale of individual marshes and mudflats (the frequency the WRMP is discussing), to 10 years at the subembayment scale (e.g., far South Bay), to several decades at the scale of the whole Bay. However, the theoretical time scales are confounded by data accuracy. The time period between surveys has to be long enough for the uncertainty in the survey to be small compared to the size of the change (erosion and deposition) being measured or modeled (Foxgrover et al., 2019). With instrumentation getting better, particularly instruments involved with the positioning of the boat and determining the absolute vertical position of the sensor head, uncertainty is lessening over time. If the bathymetric change is large enough, a 10-year time frame would most likely be long enough to compute a “real” change. A 10-year time frame could also be meaningful for areas with smaller changes (for example mudflats and subtidal shoals) if the analysis is done over a larger area so that random errors from individual soundings are averaged out. Another challenge with shorter time intervals is the relationship of the survey date to a disturbance event, such as a few very wet years, a dry decade, an earthquake, a storm surge, or a levee breach. Such disturbances may cause ephemeral erosion (e.g., Foxgorver et al., 2019) or deposition that may not be representative, and processes associated with earthquakes and storm surges may not be well parameterized in models of the Bay.

In summary, the RMP is about to receive a Bay-wide reanalysis of bathymetric change (Fregoso et al., in preparation). The modelers gathered at the October 2019 RMP SedWG Modeling Workshop anticipated using this data immediately to update their bed boundary controls within Bay models. With improving technologies and ongoing wetland restoration opening up further net permanent sediment sinks on the Bay margin, it is recommended that bathymetric surveys be repeated in about 10 years.

3.3.4 Sediment removal by sand mining and dredging

Extraction of sediment through navigational dredging and sand mining has been carried out for decades (Barnard et al., 2013b). Volumetrically, it amounts to several million cubic yards of sediment on average per year. In relation to the sediment budget of the Bay, extraction of sediment is a relatively large budget term (Schoellhamer et al., 2005). In theory, the effect of sediment extraction on the San Francisco Bay and coastal system is straightforward. If more sediment is removed than supplied, a negative sediment budget arises and less sediment is available to be supplied to the coastal system. This may be particularly concerning for sand-sized sediment that are important for the maintenance of beaches and dune systems on the California Coast but also within the Bay. However, an important assumption underlying this statement is that the entire Bay-Delta forms a connected morphological system, therefore sediment removal in the Bay will lead to a reduced sediment supply to other parts of the Bay or to the outer coast. Such an assumption is not necessarily valid. It is quite possible that sediment extraction leads to a deficit in the Bay sediment budget but that the increased accommodation space may lead to increased silt and clay accretion that would have otherwise flowed offshore. As a result, the sand balance of the surrounding areas or the coast may not be impacted negatively. Learning more about these processes is the subject of the BCDC/SCC sand sediment science studies that are planned for 2021 and 2022.

Information on sediment extraction is also important for making estimates of bedload and coarse sediment supply to the Bay from both the Central Valley and local small tributaries around the nine-county Bay margin. For example, estimate of bedload into the Bay at Mallard Island have been made by subtracting the volume of sediment removed from mining and dredging from bedload transport estimates made using Van Rijn (1984) equations at two upstream sites which are less tidally affected (Sacramento River at Rio Vista (SRV), and San Joaquin River at Jersey Point (SJJ), both located 25 km upstream of Mallard Island). Marineau and Wright (2014) used this as a basis for computing sand exiting the Delta for WYs 1997-2010. In a similar fashion, the few sediment budgets that have been done for local tributaries have all either directly or indirectly benefited from a knowledge of local sediment extraction (Ganju et al.; 2004; Downing-Kunz and Schoellhamer 2013; 2015; SFEI-ASC, 2016; Shellenbarger et al., 2015; Foxgrover et al., 2019).

BCDC oversees the permitting and databases that report on sediment extraction from San Francisco Bay. The majority of data on sediment extraction through navigational dredging can be obtained from the DMMO database on an annual basis and the data includes grain size information. Although data quality varies prior to 2000, reliable data exists for the more recent period. BCDC also keeps records of sand extracted by mining leases. Because mining varies in relation to the commercial market, annual volume is variable. Mining data are potentially available from the 1970s may be of spurious quality but are more reliable from 2004 onwards. Grain size data are more reliable beginning 2015 and are also available from other sources (e.g., USGS; Patrick Barnard). Mining data are submitted to BCDC on a quarterly basis and collated by BCDC staff in excel spreadsheets.

In summary, sediment extraction from San Francisco Bay is a large component of the annual sediment budget. It has the potential to impact the movement of sand from one embayment to another and to the outer coast. It is also used to help make estimates of sediment supply to the Bay. For the most part, the data is readily available either from the DMMO database or from BCDC staff and includes information on grain size. There are no immediate recommendations but some may emerge as a result of the planned BCDC/SCC sand sediment science studies.

3.4 Data gaps and needs associated with Management Question 4: How much sediment is passively reaching tidal marshes and restoration projects and how could the amounts be increased by management actions?

Tidal marshes are critical habitat to important native species and function as natural filters of pollutants and nutrients as they enter the Bay from the urban watersheds (Goals Project, 2015). Wetland elevation can decrease as a consequence of organic matter decomposition, compaction, and erosion and can increase with additions of roots and rhizomes and deposition of mineral and organic particles. The net rate of accretion will depend on the rate of mineral sedimentation and primary productivity which in turn depends on the relative elevation, depth of flooding and suspended sediment concentration (Morris et al., 2016). As sea-level rise accelerates, the saline tidal marsh and mudflats of the Bay will increasingly rely on the supply of fine mineral sediment to maintain their elevations with respect to the tide, although there is significant uncertainty in both the future rates of sea-level rise and the available sediment supply (Lacy et al., 2015; Dusterhoff and McKnight, 2020). Preliminary estimates of existing supplies relative to anticipated future demands for tidal marsh protection and restoration in the Bay indicate substantial deficits in supply (Dusterhoff and McKnight, 2020), although these vary according to the proximal watershed (Stralberg et al., 2011; Swanson et al., 2014; Rosencranz et al., 2018). It is therefore important to understand how the sediment supply varies around the Bay and how the sediment reaches the marshes.

Sediment supply information is available (SFEI-ASC, 2016; Schoellhamer et al., 2018) and is being used to help guide which mature marshes and restoration projects have the greatest chance of survival and success (SFEI and SPUR, 2019), as well as indicate where and when management actions may be required (Goals Project, 2015; PBCS, SFEI, and MC, 2019). Luckily, an understanding of how sediment reaches each march is conceptually well known (Krone, 1979). Krone's model describes a seasonal cycle of fine sediment delivery from the Delta and tributaries during large, winter freshwater flows that create a large pool of erodible sediment within the channels and subtidal shallows. During the following summer months, local winds generate wind-waves that resuspend bed sediment in the subtidal shallows for transport by tidal currents onto marsh surfaces. The general conceptual model of transport into the marshes is that suspended sediment from the Bay is conveyed to the marsh along tidal channels on tides that inundate the marsh plain (e.g., Collins et al., 1986). The sediment tends to settle rapidly as it is filtered by marsh vegetation, such that the sediment is largely confined to the immediate margins of the channels. The concentration of suspended sediment in the waters that inundate the marsh, and the duration of inundation, decrease upstream and with the distance across the marsh plain away from the channel banks. The rate of mineral accretion depends on the suspended sediment concentration, the depth of water over the marsh, and the period of slack water (Swanson et al., 2014).

In the time since these conceptual models were developed, there has been significant work in the Bay to monitor and model relevant sediment dynamics. For instance, Lacy et al. (2015)

measured a high bayward net suspended sediment flux in two tidal creeks during king tides and a landward but lower flux during neap tides and wind-wave events. Lacy et al. (2020) found averaged accretion over four years was twice as great across the marsh edge compared to locations adjacent to a tidal creek indicating that marshes are not solely dependent on tidal channels for sediment supply. They also found a landward progression of physical processes away from the marsh edge dependent upon tide range, wave climate, and vegetation type, the net result being that persistent waves and increased sediment trapping in summer accounts for more sediment supply across the marsh edge than winter storms (Lacy et al., 2020). These studies indicate a significant temporal variation in the magnitude, direction, and the pathway of sediment into the marsh from the standard conceptual model.

Prediction of sediment availability to marshes can be improved by better understanding the processes by which sediment enters the marsh and by accounting for spatial and temporal variability of concentrations in subtidal shallows. Much is known about marsh deposition processes and rates from the work described above, but information weaknesses remain: Do particle size and settling velocity change significantly as Bay waters flood onto marshes? Particle size may increase through flocculation due to relatively quiescent marsh conditions, or turbulent flow through vegetation may break up flocs, decreasing particle size. Either process would affect the amount of sediment retained on the marsh. How does marsh edge type (sloped vs. scarped) affect sediment delivery across wave-exposed marsh margins? How will sediment delivery across wave-exposed marsh edges change with sea-level rise and decreasing sediment supply?

A universal model that will be useful for marsh restoration sites across the Bay will have to address the relative roles of site-specific variables in sediment deposition, such as creek dynamics, marsh edge morphology, vegetation type, wave exposure, and seasonal variations (Lacy et al., 2020). These models will also have to account for different wave regimes, marsh morphology, and vegetation characteristics in different parts of the Bay. To generate data for the calibration and validation of numerical models and to further develop conceptual models will require longer-term observations than we currently have to capture long-term trends, events, and seasonal changes. So far the observations in the Bay have been mainly limited to a few sites in the North and South Bay. The USGS has monitored a number of short-term (6-10 week) subtidal shallow studies in San Pablo Bay and in the South Bay:

- San Pablo Bay subtidal shallows: 4 stations -1 and -2 m MLLW 2014-2015, 3 stations -1 to +0.5m MLLW in 2011 (MacVean and Lacy, 2014; Lacy and MacVean, 2016; Lacy et al., 2018).
- Shoals south of San Mateo Bridge (Brand et al., 2010, 2015; Lacy et al., 2014)

The WRMP is developing a pilot program to monitor mature and restored tidal marsh habitat at a network of key marshes throughout the Bay. These benchmark sites are a combination of highly valued, mature, high-elevation marshes and areas where future large-scale tidal restoration is likely to happen, in order to inform the design and adaptive management of these marshes and empirically estimate the adequacy of their suspended sediment supplies. The WRMP conceptual model assumes that SSC in the feeder channels of the marsh and at the marsh edge are boundary conditions and the WRMP intends to rely on the RMP for the monitoring of sediment fluxes in these subtidal shallow areas. Key to this approach is an improved understanding of how to predict SSC at the marsh edge and flux into the marsh from SSC measured in subtidal shallows.

In summary, the conceptual model for movement of sediment into marsh channels and onto marsh plains is well developed. However, there have been relatively few measurements of this process and the few measurements that have been made indicate wide variability between marshes and march edge types. And as study progresses, more questions are emerging in association with particle size, settling velocity, flocculation, marsh edge type (sloped vs. scarped) and how these factors will change with sea-level rise or changes in sediment supply. Future measurements of the sediment dynamics in the subtidal shallow parts of the Bay should be coordinated with the WRMP studies in the benchmark sites. This will require the deployment of fixed instrumentation for suspended sediment concentration, waves and currents for extended periods in both the summer and winter adjacent to the framework sites and coordinated with the WRMP studies within the marsh.

3.5 Data gaps and needs associated with Management Question 5: What are the concentrations of suspended sediment in the Estuary and its subembayments?

Information on SSC in the Bay has been collected for decades and as such the Bay is generally rich in data on SSC. At selected bridges, promontories, in sloughs and other tidal margin areas, the RMP special studies program has been collaborating with the USGS to continuously monitor suspended sediment concentration (SSC) and turbidity (beginning 1991), dissolved oxygen (beginning 2012), temperature, salinity, and water level (all beginning 1988) (Ruhl et al., 2001; Schoellhamer et al., 2002; Schoellhamer et al., 2018). In addition, some stations have periodically been supported by acoustic instruments to measure velocity and grain size. On occasions, cross-sections have also been characterized using 24-hour boat-mounted instrumentation (Shellenbarger et al., 2013). A number of bridge cross-sections (Dumbarton, San Mateo, Richmond, Carquinez (Hwy 80), Benicia (Hwy 680), and sites near Alcatraz Island and off Mallard Island (co-located with the DWR instrument package) have also been monitored (Schoellhamer et al., 2002). Although each site has a unique length of record, these time-series data provide the longest continuous record of spatial and temporal variations of SSC throughout the Bay and have been used as the basis for understanding sediment and contaminant transport processes, sediment availability for restoration, light attenuation in relation to primary productivity, dredging needs, and development decisions (for example the SFO runway extension) (Schoellhamer et al., 2008; David et al., 2009; McKee et al., 2013; Schoellhamer et al., 2018).

There is good spatial coverage of SSC from the RMP base program and a very good understanding of temporal variation from the RMP-USGS collaboration. The remaining weaknesses largely reflect the difficulty in obtaining data in shallow areas (shoals, mudflats, and wetland sloughs). Although there are data in these areas from the RMP base program and the Margins special study, these are snapshot data; there are only a few examples of temporally resolved data on mudflats (Kranck and Milligan, 1992; Lacy et al., 2003; McVean et al., 2014). For example, Kranck and Milligan (1992) studied suspended sediment in-situ floc size distributions, constituent grain size distributions, total concentrations, and average particle densities at five depths over 11 hours on the edge of San Pablo Strait in San Pablo Bay. They found that the settling rates corresponding to the modal floc diameters were generally related to the maximum disaggregated diameters, but that turbulence appeared to limit floc size in the coarsest samples. They found that both the floc and disaggregated grain size appeared to vary with total concentration, and proposed that flocs are relatively stable entities during cycles of settling and resuspension. Data on settling velocity and flocculation of different grain sizes for a variety of shoal environments are needed (RMP SedWG Modeling Workshop, October 2019).

Waves and tidal currents re-suspend sediment from the erodible sediment pool. In the subtidal shallows, SSC depends more strongly on wind speed and direction than tidal energy due to the importance of wind-wave resuspension (Schoellhamer, 1996; Lacy et al., 1996; Brand et al., 2010). Wave events are correlated with significant SSC variation between locations with higher concentrations closer to the Bay shore than concentrations closer to the subtidal channels (Brand et al., 2010). The onset of sediment resuspension is dependent on wave shear stress, which is a function of water depth, wave height, and surface roughness, although some models seem to be insensitive to roughness (RMP SedWG Modeling Workshop, October 2019). In the South Bay, most resuspension events observed by Brand et al. (2010) occurred during flood tides that followed wave events at low water, when waves could reach the channel bottom and mobilize the bed. Since the bottom stress due to wave motions at low water exceeded the peak stresses induced by tidal flow, Brand et al. (2010) hypothesized that the wave motions at low water resuspended sediment into the lower part of the water column. Suspended sediment was later mixed higher up the water column by the tidal stresses of the flood tide. The observation of elevated resuspension for several tides during calm periods following wind-wave resuspension shows that mechanisms, such as loosening of sediment from the seabed, can perform an important role. The ability to maintain suspended sediment over multiple tidal cycles, or easily resuspend sediment, will be strongly dependent on the sediment characteristics at the site, with finer-grained sediment staying suspended longer. Relevant processes can vary; for example, recently published data from the shoals of San Pablo Bay (Allen et al., 2019) indicate settling velocity is highest during slack tide; while data from Dumbarton Bridge indicate settling velocity is lowest during slack tide (Livsey et al., 2019).

Direct measurements of SSC or estimations using a turbidity surrogate are needed in these environments to calibrate models, specifically continuous SSC in the subtidal shallows and at the subembayment boundaries (RMP SedWG Modeling Workshop, October 2019). However, since it is near impossible to collect SSC data in all the differing mudflat environments around the Bay, models will be needed. The data could also be augmented by the use of satellite based remote sensing technologies which are continuously increasing the resolution with which coastal processes can be measured (Fringer et al., 2019). Since SSC at any moment in time and space is the result of a series of complex processes associated with energy fluctuation over a wide range of time scales and physical properties that vary tidally and seasonally, data to support estimation of SSC using models will necessarily include diurnal and seasonal tides, water temperatures, winds and freshwater flows, water depth, grain size, bulk density, organic carbon, bioturbation, and flocculation.

In summary, information on SSC in the Bay has been collected for decades. Information includes a number of continuous monitoring sites and the RMP snapshot data. The remaining weaknesses are in shallow areas (shoals, on mudflats, and in wetland sloughs). In these areas, data on settling velocity and flocculation of different grain sizes in a range of representative environments are lacking and needed.

4. Monitoring/Modeling Recommendations

4.1 Recommendations for addressing Management Question 3

4.1.1 Tributary supply

Monitoring suspended sediment and bedload at large Bay tributaries

We recommend maintaining or adding bedload data collection at existing monitoring sites (Alameda Creek, San Lorenzo Creek, and Guadalupe River). In addition, given the magnitude of estimated sediment supply, the lack of recent data, and the need for geographic representation in countries around the Bay to cover the combined effects of microclimates and differing geological terrains, we recommend adding SSC monitoring the following sites (and bed load where possible):

a. Sonoma Creek
b. Napa River
c. Walnut Creek
d. San Francisquito Creek

Monitoring SSC and bedload at mudflat/marsh-coupled tributaries

Small tributaries should also be included that have a significant effect on local mudflats and marshes. Examples include:

a. Wildcat Creek
b. Novato Creek
c. Arroyo Corte Madera del Presidio
d. Belmont Creek
e. Atherton Creek

Measurements of fluxes in the fluvial reaches of flood control channels

Flood control channels (FCCs) function both as sediment sources and sinks. Since FCC dynamics have replaced those of natural tributaries in many areas, recording systematic measurements of sediment storage and removal and collecting strategic measurements of fluxes at FCC tidal mouths will increase understanding of tributary sediment loading to the Bay. Examples covering a reasonable variety of geography could include:

a. Walnut Creek
b. Napa River
c. Novato Creek
d. Alameda Creek
e. Coyote Creek
f. San Francisquito Creek
g. Belmont Creek

Dynamic Simulation Model of Loads at Unmonitored Tributaries

We recommend the development of a dynamic simulation model to estimate sediment load to the Bay for unmonitored areas of the watershed. This would take the place of the current regression-based statistical extrapolation techniques (McKee et al., 2013; Schoellhamer et al., 2018). The model will need to have the ability to simulate storage in the major flood control channels and would need to be supported by maintenance removal data (or some assumptions about removal rules based on consultation with channel managers). Given the parallel needs of other workgroups (nutrients, contaminants of emerging concern, and SPLWG), we recommend coordination rather than primary development. Recently, the SPLWG has completed a modeling strategy to support trends evaluation (Wu et al., 2018) and a modeling implementation plan (Wu and McKee, 2019) that lays out the plan for development of a Hydrological Simulation Program - Fortran (HSPF) model for the watersheds that drain to the Bay from the nine adjacent counties. We recommend that the SedWG proactively budget for oversight and, if necessary, additional financial support in 2022 or 2023 once this modeling effort matures.

4.1.2 Delta sediment supply

As discussed in the previous sections, uncertainties remain about the current accuracy and validity of the proxy method developed by McKee et al. (2006) for the computation of delta suspended sediment load, and the lack of robust bedload measurements. The following studies are recommended for resolving flux from the largest single sediment source to the Bay:

Maintain the existing USGS SSC program (funded by the RMP-based program)

Collect continuous time-series of turbidity data using the existing probes mounted at two depths at the end of the pier at Mallard Island and convert these to SSC and publish annually using established methods (e.g., Buchanan et al., 2018). Feed those data into the computational scheme developed by McKee et al. (2006) to estimate daily and annual loads. This is usually done about May of each year and is often done to support the publication of the Pulse (e.g., page 70, SFEI, 2019).

Spatial variations at Mallard Island over tidal cycles

Collect a new data set on the vertical and horizontal variation of SSC and velocity over 25-hour tidal cycles during a variety of spring and neap cycles during wet and dry conditions (including a wet season storm event) in the 950 m cross-section adjacent to Mallard Island. Use this data to recompute/verify the dispersive-advective flux ratio reported by McKee et al. (2006). Update the computation method as needed.

Bedload measurements at Mallard Island

a) Consult with bedload and modeling experts to develop a proposal and implement a reliable bedload estimation program that will likely involve some level of refinements of the monitoring and modeling techniques proposed above.
b) Collect measurements at Mallard Island of bedload during various flow events and tidal conditions. Compute long-term bedload estimates of sand supply to the Bay from the Central Valley using an appropriate surrogate proxy measurement. Examples could be suspended sediment flux or Delta outflow (Dayflow model). This will help resolve modeled estimations of sand flux into the Bay from the Delta (described below).

4.1.3 Flux at the Golden Gate

As discussed in the previous sections, there are no bedload flux estimates for the GG and suspended load estimates are limited to a few field deployments due to a lack of a verified surrogate relationship. The following studies were recommended by Downing-Kunz et al. (2017) although there maybe some new recommendations to consider based on that current modeling study being carried out by McWilliams et al (report due in the 1st quarter of 2021):

Model suspended sediment flux

a) Develop and calibrate a 3D numerical model to estimate suspended sediment flux in the cross-section at the GG Bridge that is temporally resolved at the time scales of the available measured data.
b) Develop a relationship between suspended sediment flux and relevant parameters that are readily available such as SSC at Alcatraz (2003-present) and freshwater flow, similar to the approach of Erikson et al. (2013) to allow estimation of suspended sediment flux at times other than the duration of the model runs. This would involve a few steps.
c) Compare numerically modeled and measured fluxes to derive a regression equation. Explore other parameters such as wind direction and speed, flow, or tide to explain residuals and, if possible, add parameters to the regression model to improve predictability. Use the best regression to develop estimated time series of suspended sediment flux for a longer duration model run.

d) Compare the estimated time series of suspended sediment flux to relevant parameters that are readily available such as SSC at Alcatraz and freshwater flow, similar to the approach of Erikson et al. (2013) to derive the surrogate equation.

Make additional empirical observations of flux at the Golden Gate Bridge

Use the model and surrogate results to identify conditions for additional measurements during large watershed outflow events. Ideally, multiple days of measurements would be made for a single storm over the duration of the hydrograph (e.g., the rising limb, peak, and falling limb) to provide additional data to understand the nature of sediment transport through San Francisco Bay from the watershed to the ocean.

4.1.4 Flux between subembayments

Measure flux at key cross-sections (Benicia Bridge, Richmond/San Rafael Bridge, and Dumbarton Bridge). Deploy acoustic, doppler, and turbidity instruments for measurement both in-situ (continuously) and by boat (periodically: spring neap, wet, dry seasons) at priority bridge cross-sections

a) Benicia Bridge: Previous methods used to compute suspended sediment flux at these locations are based on field observations from the early 2000s, which are now outdated. Additionally, these observations did not consider the effects of flocculation and secondary circulation. Recent work funded by a SEP indicates that the magnitude and direction of flux at the Benicia Bridge may need to be modified. A re-analysis of previous data is needed to update and refine the sediment-flux estimates for Suisun Bay. Additional data collection (continuous in situ and spring-neap-wet-dry season boat-based 24-hour deployment of acoustic doppler and turbidity instruments coupled with SSC sampling and flocculation experiments) and integration of new and existing field observations with a modeling effort is recommended;
b) Richmond/San Rafael Bridge: This is a large and difficult cross section. However, flux data here would nicely constrain the sediment budget for San Pablo Bay and help to support models designed to estimate flux at the Golden Gate Bridge. Additional measurements (continuous in situ and spring-neap-wet-dry season boat-based 24-hour deployment of acoustic doppler and turbidity instruments coupled with SSC sampling and flocculation experiments) at Richmond/San Rafael Bridge coupled with a modeling effort are recommended;
c) Dumbarton Bridge: Validation of sediment transport models on long-term sediment flux measurements and flocculation data from 2009-2011, 2013-2016, and 2018-2019 would provide a rigorous test-case for the application of sediment transport models to predict suspend-sediment fluxes in the Estuary. Sediment transport models that aim to include flocculation could utilize flocculation data for model calibration and validation. Additional data collection (continuous in situ and spring-neap-wet-dry season boat-based 24-hour deployment of acoustic doppler and turbidity instruments coupled with SSC sampling and flocculation experiments) during a wet year may be warranted if the model results

suggest that is necessary. Compare model results to measured fluxes and identify parameters for a proxy-regression model to estimate long term fluxes for the entire turbidity record.

4.1.5 Flux within subembayments

Measure flux in margin tidal channels

Current data weaknesses include a lack of long term studies to determine net sediment trapping, a lack of coarse sediment information, and data gaps on some margins that will hamper the calibration of models to support wetland restoration design. Reflecting these gaps, the following recommendations are made:

a) Initiate studies on tidal channel systems of the Bay margin generally following the methods of Downing-Kunz and Schoellhamer (2013) but adding a bedload (coarse sediment component). Select from the following possible locations: South Bay (Alameda Creek for example), western San Pablo Bay (Novato Creek for example), San Pablo Bay (Napa River for example), and coastline of Contra Costa County (Walnut Creek for example).
b) To better determine long term sedimentation processes, either
    i) Reoccupy a previous study site using the methods of Downing-Kunz and Schoellhamer (2013) (for example, either Corte Madera Creek or Alviso Slough) with the objective of capturing wetter years in the data set or
    ii) Work with the Flood Control Agencies to develop additional sediment budgets (fluvial sediment supply-sediment deposition-sediment removal = long-term net sedimentation) following the methods of SFEI-ASC (2016)

4.1.6 Sediment sinks and reservoirs in the Bay - Bathymetry

Develop a Bay-wide bathymetric 3D numerical model

Develop a model suitable to predict changes in bathymetry at the scales of subembayments, mudflats, tidal channels, and individual wetlands. This model can be focused and calibrated for specific use in smaller-scale projects and areas where site-specific data may be lacking.

Resurvey Bay bathymetry

In order to support baywide modeling in general, changes in bathymetry must be recorded across the whole Bay, or those parts most subject to change and near sites of concern, such as large restoration projects. Bathymetric data should also be merged with surveys of intertidal zones such as mudflats and updated at a minimum of every 10 years.

Complete bathymetric change analysis

Following the methods of Fregoso et al., 2020 (in preparation), complete another bathymetric change analysis in about 12 years (2032) to provide checks on the model described above and to support other Bay modeling (RMP SedWG Modeling Workshop, October 2019) and act as a long-term control on model parameterization.

4.2 Recommendations for Addressing Management Question 4

The Wetland Regional Monitoring Program (WRMP) is developing a pilot program to monitor sedimentation processes and its impact on marsh habitats at a series of benchmark sites around the Bay. The monitoring is both to better understand sediment and marsh processes and also to develop and calibrate models of future conditions. Benchmark sites are intended to be associated with the complementary network of stations of the RMP to monitor salinity, tides, and suspended sediment in the major embayments. The WRMP will focus on processes that occur within the marsh and on the mudflat itself with the assumption that the RMP will provide data on suspended sediment processes in the adjacent subtidal shallows. The was recommended following discussions with the WRMP team.

4.2.1 Coordination of subtidal shallow Bay monitoring with the WRMP framework sites

Form a small focus team with participation from the RMP and WRMP to coordinate the monitoring of the WRMP framework sites. The team would develop a joint research plan to monitor sediment flux into the marshes through channels and across the marsh edge both for the purpose of understanding processes and to calibrate indicators of future conditions. The team must jointly agree on the location of the benchmark sites and the frequency of measurements. The WRMP suggests that sites should be located in each of the subembayments - Suisun Bay, San Pablo Bay, Central Bay, South Bay, and Lower South Bay. Each of these represents a reasonably distinctive position along the main estuarine salinity gradient, a different tidal range, different sediment supply dynamics, and different plant and wildlife communities.

4.2.2 Combined studies with the WRMP

Form a small focus team with participation from the RMP and WRMP to develop a series of studies on how marshes in different parts of the Bay respond to future changes in sea level and sediment supply. Questions to be addressed could include: a) How do sediment dynamics in channels, mudflats, and marshes respond? b) How connected are the mudflats and marshes to the baywide sediment budget? c) How do channel width and depth evolve, and how does that influence supply to the mudflat? d) Do mudflats accumulate more sediment at the expense of marshes? e) Do certain marshes continue to accrete sediment and grow, while others drown or erode? f) Do particle size and settling velocity change significantly as Bay waters flood onto marshes?

Particle size may increase through flocculation due to relatively quiescent marsh conditions, or turbulent flow through vegetation may break up flocs, decreasing particle size. Either process would affect the amount of sediment retained on the marsh. Further questions include: g) How does marsh edge type (sloped vs. scarped) affect sediment delivery across wave-exposed marsh margins? and h) How will sediment delivery across wave-exposed marsh edges change with sea-level rise and decreasing sediment supply? Coupled with these observational studies, we recommend development of a model that will be universally useful for marsh restoration sites across the Bay. It will have to address the relative roles of site-specific variables in sediment deposition, such as creek dynamics, marsh edge morphology, vegetation type, wave exposure, and seasonal variations and will account for different wave regimes, marsh morphology and vegetation characteristics in different parts of the Bay. Such a model might need to be supported by a few select sites with longer-term observations to capture long-term trends, events, and seasonal changes. Reoccupation of past sites may be a good starting point:

- San Pablo Bay subtidal shallows
- Shoals south of San Mateo Bridge

4.3 Recommendations for Addressing Management Question 5

4.3.1 Continuous SSC monitoring in the subtidal shallows and subembayments

Continuous monitoring of turbidity and suspended sediment concentrations will be crucial in informing models aimed at resolving sediment flux over a variety of timescales, from tidal variations to seasonal climate patterns. Additionally, the long-term continuous measurement will be more likely to capture rare high-magnitude runoff events that may potentially have a significant impact on fluxes and sedimentation. In order to capture bay-wide water column SSC, existing sensors must be regularly calibrated to refine relations between turbidity and SSC. Continuous SSC monitoring should utilize existing sites such as USGS sensors at bridges and subembayment cross-sections and the Nutrient Management Strategy (NMS) Moored Sensor program in subtidal shallows and sloughs within the South Bay. The network of permanent sensors should be expanded, however, to include more subtidal shallows throughout the rest of the Estuary particularly located close to the WRMP framework sites (see above).

4.3.2 Use satellite imagery to analyze turbidity and SSC

High-resolution satellite imagery has the potential to serve as a proxy for the spatial variability of turbidity in the Bay, and, by extension, suspended sediment. Continuation and expansion of studies similar to work by Oliver Fringer and Joe Adelson will help establish quantifiable relationships between remote sensed turbidity and sediment concentrations in the water column and inform where to collect water column data.

4.3.3 Characterize differences in sediment properties in shallows across the Bay

Measure spatial relationships between SSC and bed shear stress in the shallows

Primary data weaknesses pertain to a lack of spatial coverage and whether similar relationships between SSC and bed shear stress apply in different parts of the Bay. As such, short term studies should be undertaken with measurements of SSC, waves, and currents at different bed elevations at multiple stations on the eastern shoals north of the Dumbarton Bridge and north of the San Mateo Bridge. These studies could help determine if there are consistent relationships between SSC and bed shear stress between different subembayments or are differences due to bed properties, or flocculation dynamics. In addition, spatial mapping and temporal variations in grain size, settling velocities, bed erodibility, and flocculation is needed to calibrate models.

Bed erodibility characteristics

Undertake broad mapping of grain size, bed roughness, and critical shear stress in different subembayments during different seasons. This will help determine the appropriate values of critical shear stress and sediment erodibility to use in modeling sediment dynamics in the shallows. In addition, develop biological or physical indicators to predict variations in bed erodibility that are easier to measure building on the work by the USGS in San Pablo Bay and Suisun Bay.

Settling velocities

Undertake additional measurements of settling velocities and flocculation during different tidal and wave conditions, seasons, and in different subembayments (Allen et al., 2019; Livsey, 2019). This will help determine the appropriate particle size and settling velocity to use in modeling sediment transport in the shallows, allow the conversion of turbidity data to SSC, and help develop a predictive relationship for settling velocity/particle size in the shallow .

5. Ranked Monitoring/Modeling recommendations

The newest of seven workgroups, the SedWG was formed in 2016 by the RMP Steering Committee to address sediment delivery, transport, dredging, and beneficial reuse. The SedWG is guided by five management questions:

1. What are acceptable levels of chemicals in sediment for placement in the Bay, baylands, or restoration projects?
2. Are there effects on fish, benthic species, or submerged habitats from dredging or placement of sediment?
3. What are the sources, sinks, pathways, and loadings of sediment and sediment-bound contaminants to and within the Bay and subembayments?

4. How much sediment is passively reaching tidal marshes and restoration projects, and how could the amounts be increased by management actions?
5. What are the concentrations of suspended sediment in the Estuary and its subembayments?

Balancing information development across this wide variety of core questions is a challenging endeavor within one oversight structure like the RMP SedWG, let alone coordinating across all the other groups currently working on some aspect of sediment in San Francisco Bay (WRMP and BCDC, and other RMP workgroups such as NMS and SPLWG). However, it is hoped that the prioritized recommendations that follow in Table 2 will serve as a foundation to enable further discussion and collaboration between these subgroups and organizations and importantly avoid duplication effort. It should also be noted that there are many more recommendations in section 4 of this report that have not been prioritized at this time. Many of these have been prioritized as medium and will likely be a source for discussion and prioritization at future SedWG meetings.

The summary in Table 2 is based on discussions at the March 2020 RMP SedWG meeting. The studies shown for the priority recommendations will help meet the data needs but more work needs to be done to close those critical data gaps. For example, although a modeling study was funded in 2020 to estimate fluxes at the Golden Gate for a 3 month period (McWilliams et al in preparation), it is likely that further modeling of sediment flux in this cross-section will be initiated in the future once further empirical data become available or improvements in models or computing power evolve. Ultimately, for the Golden Gate cross-section, an estimate of long term flux is needed to close the Bay sediment budget that will likely combine the use of a proxy with modeling. Thus, it is very likely that the SedWG may again prioritize a modeling study at the Golden Gate in the next 5-10 years. In addition, although there have been studies funded on settling velocity and flocculation of different grain sizes for a variety of shoal environments (Allen et al., in preparation) and sediment flux into marshes and depositional processes on marsh surfaces in relation to differing edge types and vegetation environments (J. Lacy and K. Thorne 2021 Special Study), both of these studies were located in the South Bay. Similar data are needed in other Bay environments and locations, and this has been identified by modelers as important data for parameterizing and calibrating models of sediment processes in relation to our key management questions. It is likely that these types of studies will need to be repeated multiple times over the next 5-10 years to expand data sets. Once these data sets mature (or in parallel), modeling studies will need to be initiated to further explore data weaknesses.

There are also priority recommendations that have not yet received funding. The SedWG will have to decide whether to continue to focus on filling out the data sets or modeling capabilities to address a few priority recommendations at a time, or to broaden the scope of work over the next few years to a wider variety of studies. This decision may be influenced by opportunities to collaborate and as well as available capacity.

Table 2 - Priority recommendations for additional sediment studies over the next five years.

Conceptual Model Element	Action Category	Priority Recommendation	Relevant Studies	Funding Source	Year
Loading to the Bay	Small tributaries sediment supply	Continue loads monitoring at existing tributary sites	Alameda, San Lorenzo, and Guadalupe loads (USGS sites)	Alameda County PW / Valley Water	WY 2020 & 2021
		Add monitoring at new tributaries for greater spatial coverage	Belmont, Arroyo Corte Madera del Presidio, Novato, and Walnut	SEP	WY 2020 & 2021
Transport Pathways	Flux at x-sections in the Bay	Improve the information for Benicia Bridge x-section for 2002-2019	Livsey & Downing-Kunz	SEP	Expected in 2021
	Flux on shoals and into wetlands	Initiate shoal flux studies near reference marshes	South San Francisco Bay: Lacy & Thorne	RMP special study	Expected late 2022
		Model suspended sediment flux between the Bay axis and shallows			
		Model changes in sediment delivery for future conditions			
	Golden Gate Bridge flux	Model suspended sediment flux at the Golden Gate	McWilliams et al in preparation	RMP special study	Report expected in Q1, 2021
		Empirical observations of flux at the Golden Gate Bridge	Winter high flow in response to a storm	RMP discretionary	Reactionary
		Develop a proxy for estimating long term SSC flux at the GG Bridge			
	Whole Bay	Developing tools to track sediment sources, sinks, and pathways	On the SEP list		
Sinks and Reservoirs	Bathymetric change	Filling bathymetry bdta gaps	On the SEP list		
Sediment Character	Bed character	Bed erodibility estimates in at a variety of locations around the Bay			
Bay Water Column Character	SSC in the water column	Data on settling velocity and flocculation of different grain sizes for a variety of shoal environments	South San Francisco Bay: Allen et al.	SEP	Report expected late 2021
		Continuous SSC monitoring in the shallows and subembayments	On the SEP list		
	SSC in the water column	Use satellite imagery to analyze turbidity and SSC			
Conceptual models	Whole system	Sediment dynamics conceptual model and uncertainty analysis	Dusterhoff et al.	SEP	Expected late 2021

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