Sediment Supply to San Francisco Bay, Water Years 1995 through 2016: Data, trends, and monitoring recommendations to support decisions about water quality, tidal wetlands, and resilience to sea level rise

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List of Acronyms and Units

ADCP	Acoustic Doppler Current Profiler
BCDC	Bay Conservation and Development Commission
cfs	Cubic feet per second
DWR	California Department of Water Resources
EPA	U. S. Environmental Protection Agency
FC 2.0	Flood Control 2.0 (see floodcontrol.sfei.org)
ft	feet
GIS	Geographic Information System
HOT	Head of tide
IAV	Invasive aquatic vegetation
kg	Kilogram
km	Kilometer
km^3	Cubic kilometers, one thousand million cubic meters (10^9 m^3)
L	Liter
mg	Milligram
Mm^2	Million square meters
Mm^3	Million cubic meters
Mt	Million metric tonnes (1 metric tonne = 1,000 kg)
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
RMP	Regional Monitoring Program for Water Quality in San Francisco Bay
RWSM	Regional Watershed Spreadsheet Model
S	Salinity (psu, practical salinity units)
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
SFEI	San Francisco Estuary Institute
SJJ	San Joaquin River at Jersey Point
SRV	Sacramento River at Rio Vista
SSC	Suspended-sediment concentration (mg/L)
t	Metric tonne = 1000 kg = 2,204.6 pounds
TSS	Total suspended-solids concentration (mg/L)
USACE	U. S. Army Corps of Engineers
USDA	U. S. Department of Agriculture
USGS	U. S. Geological Survey
WY	Water year, extends from October 1 through the following September 30 and is identified with the calendar year in which it ends
yr	Year

A Note on Reporting Units and Precision

The majority of sediment loads are reported in units of Million metric tonnes (Mt). The following conversions can be used to obtain loads in different units.

1 metric tonne (mt) = 1,000 kg = 1.1 US tons
1 million metric tonnes (Mt) = 10^9 kg

Factors to convert sediment mass to volume vary based upon the type of sediment involved. Fluvial sediment is generally coarser (sand and gravel) which increases bulk density. In addition, the minerals comprising fluvial sediment are denser compared to the silt and clay of Bay sediment.

- For suspended-sediment that deposits in the Bay, one can assume approximately 1 cubic yard = 0.65 metric tonnes (Porterfield, 1980).
- For bedload that deposits in channels, one can assume a conversion factor of approximately 1 cubic yard of bedload = 1.27 metric tonnes. Note, this conversion factor was based on data and observations made in San Francisquito Creek and Walnut Creek and used as representative of the small tributaries (SFEI-ASC, 2016).

Both of these conversion factors have associated uncertainty. Given the importance of being able to accurately convert between mass and volume, more research to refine these factors is needed (see recommendations in the last section on “How can sediment monitoring be improved to fill data gaps and better provide information for resource managers?”).

Results have been reported to two or three significant figures throughout the report. Two significant figures are likely the accuracy of the measurements results reported, but three figures have been used in some cases to allow for better rounding and unit conversions.

Executive Summary

Knowledge of the status and trends of sediment supply to San Francisco Bay is critically important for management decisions about dredging, marsh restoration, flood control, contaminants, water clarity (in relation to primary production), and sea level rise. Several site-specific studies of sediment supply to San Francisco Bay have been conducted, but no synthesis of recent studies is available. The purpose of this report is to synthesize the best available data and knowledge to answer a few of the key study questions related to sediment supply to the Bay (listed below).

This synthesis report was prepared jointly by the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) and the U. S. Geological Survey (USGS) with funding from both organizations. The project is meant to be a step in the development of a more comprehensive sediment management and monitoring strategy for the Bay.

What are the magnitudes and sources of fine and coarse sediment transported to San Francisco Bay?

Net sediment supply to San Francisco Bay from terrestrial sources during the most recent 22-year period (water years [WY] 1995-2016) was 1.9+/-0.8 Mt/yr (1 Mt is one million metric tonnes or 1 billion kilograms). Sixty-three percent of the sediment supply was from small tributaries that drain directly to the Bay. Net supply from the Central Valley (measured at Mallard Island) was 37% of the total supply. Bedload supply, after accounting for dredging, removals, storage in flood control channels, and errors in measurements was indistinguishable from zero. For a 30-year “climate normal” reference period of WY 1981-2010 (a period assumed to be representative of current climatic conditions), we estimate the total sediment supply would be 2.0 Mt/yr of which 70% would come from small tributaries. The delivery points are Mallard Island for sediment from the Delta and the head of tide of each small tributary or outfall for sediment from the small tributaries.

The finding that, on average, small tributaries have supplied more sediment to the Bay than the Delta is important but not new (McKee et al., 2013). During the Gold Rush and perhaps through to the 1980s, 80% or more of the supply was estimated to be from the Central Valley (Porterfield, 1980). But land and water management have continued to evolve (Krone, 1996) and the sediment wave associated with the Gold Rush has diminished (Schoellhamer, 2011). In addition, the coastal mountains of California and around the Bay are steep, tectonically active and composed of relatively erodible marine sedimentary and metasedimentary rocks, in contrast to the Central Valley watershed that is dominated by highly indurated granitic, metasedimentary, and metavolcanic rocks in the western-facing slopes of the Sierra Nevada Mountains (McKee et al., 2013). Also, water management is quite different between the Central Valley rivers and small tributaries. About 48% of the Central Valley watershed is upstream from dams that are designed to capture, delay and diminish discharge from spring snowmelt and so eliminate or damp many of the peak flows that are normally crucial for sediment transport.

Another factor contributing to the importance of small tributaries for sediment supply is the way that they deliver sediment. Annual discharge from small tributaries is very small in comparison to the volume of the Bay (around one-fifth of a Bay volume on average), and the load that small tributaries supply is delivered through hundreds of channels and outfalls via wetland sloughs to the mudflats on the margin of the Bay. Therefore, the majority of this sediment delivered from Bay Area small tributaries is more likely to be trapped in these tidal channels or the margins of the Bay. In contrast, supply from the Central Valley enters the Bay through one large river channel at the head of the estuary (functionally adjacent to Mallard Island, near Pittsburg, CA) with an average annual discharge volume that is more than twice that of the Bay.

What are the present temporal trends of fine and coarse sediment supply to San Francisco Bay?

From the Delta

Since the step decrease in suspended-sediment concentrations in WY 1999 (Schoellhamer et al., 2011), there has been no statistically significant trend in sediment supply from the Delta to the Bay. After WY 1999 there appears to be a slight downward trend that is not statistically significant. However, the possibly downward trend in load was largely driven by decreasing discharge associated with the drought during the latter part of the study period.

From Bay Area Watersheds

At this time, we are unable to conclude whether there has been a trend in sediment supply from Bay Area small tributaries collectively. Trends in sediment loads for individual tributaries could not be determined due to sparse and incomplete datasets, the spatial heterogeneity of anthropogenic changes in watersheds, and the strong influence of variable climate on erosion in the tectonically active coastal area of California. Consistent monitoring of sediment loads at a subset of representative watersheds could be used in the future to answer this question.

Between Subembayments

Erosion in Suisun Bay has been declining as it likely approaches a state of dynamic equilibrium. Over the past 15 years (WY 2002-2016), Suisun Bay was net depositional. Sediment is exported during wet years and imported during dry years. WY 2012-2016 were dry, so the period of record ends with a prolonged dry period and net sediment deposition. The higher discharges of WY 2017 (not quantified for this report) likely exported a large amount of sediment, so the WY 2002-2017 period was likely erosional. Erosion would be consistent with our estimate of mean annual long-term erosion under current conditions.

Unfortunately, a similar exercise cannot be performed for the Lower South Bay. Suspended-sediment flux data at the Dumbarton Bridge are not available over a long enough period to evaluate trends in transport. Given a 50-year plan for wetland restoration, evidence of contamination by both PCBs and Hg, challenges associated with algal productivity, and the overall linkage of sediment dynamics to these issues, we recommend further data collection to provide a better understanding of fluxes in the Lower South Bay.

What are scenarios for future sediment supply to San Francisco Bay?

From the Delta

We hypothesize that future changes in sediment supply from the Delta will be much smaller than those observed since 1850 that resulted from hydraulic mining and dam construction. Ongoing changes associated with climate change and invasive species do not appear to be significantly affecting net sediment supply at present and foreseeable sudden and rapid landscape changes are unlikely. For example, deposition in Suisun Bay was large after hydraulic mining and was followed by extensive erosion of those deposits. The rate of erosion has since been decreasing as the sediment dynamics in the Bay become more stable and this stability, compared to the late 19th and early 20th century, is expected to continue. A record flood, however, has the potential to greatly alter sediment supply. The flood of WY 2017 was rather significant and will provide an interesting reference point for trends once data are published in the spring of 2018. In addition, if the proposed use of tunnels to divert Sacramento River water to export pumps in the southern Delta is implemented, sediment supply to San Francisco Bay is predicted to decrease downstream by 8-9% (p.5.3-24, CDWR 2013).

From Bay Area Watersheds

Future changes in sediment supply to San Francisco Bay from the surrounding watersheds will be highly dependent on shifts in precipitation and air temperature (and concomitant changes in vegetation cover) associated with a changing climate. Without model-based forecasting, hypotheses about future sediment supply from the tributaries would be speculative. Fortunately, the Environmental Protection Agency (EPA)-funded *Healthy Watersheds Resilient Baylands* project, a recently-initiated regional effort, will help address this need. The project will address future sediment supply dynamics by focusing on the range of likely changes to average annual watershed sediment supply based on downscaled climate model outputs (i.e., what is the difference in supply between the driest and wettest future conditions?), and the range of likely changes to the frequency of large storm pulses that deliver watershed sediment to the Bay (i.e., what is the difference in 2-year to 100-year flood discharge between the driest and wettest future conditions?). The results can be used as a starting point for hindcasting past sediment supply and forecasting the future sediment supply to determine the relative change over previous and future decades.

How can sediment monitoring be improved to fill data gaps and better provide information for resource managers?

Maintaining and expanding regional monitoring for suspended-sediment and bedload is critical for collecting accurate data on sediment supply to the Bay. Specific options for improvements to the monitoring design have been compiled in this report. In addition to direct measurements of sediment supply, a monitoring program should also have components to measure sediment accretion/inundation in shoreline marshes as a direct measure of whether sediment supply is keeping up with demand in critical habitats. Models for watershed loads and movement of sediment within the Bay are other tools that will be needed.

The cost of all the recommended monitoring will exceed available resources and, therefore, recommended monitoring must be prioritized. Management objectives need to be clearly articulated to facilitate prioritization of these recommendations. For example, if the objective of monitoring is to improve the accuracy of the calculated sediment budget for San Francisco Bay, monitoring efforts for sources that are highest in magnitude and lowest in cost could be prioritized. If the objective is to improve a local estimate such as for a restoration project at the margin of the Estuary, sediment supply from the local watershed, even if small, and quantification of supply from the Estuary could be prioritized.

1. Introduction

Motivation and Objectives

Knowledge of the status and trends of sediment supply to San Francisco Bay is critically important for management decisions about dredging, tidal marsh restoration, flood risk management, and sea level rise adaptation. Several site-specific studies of sediment supply to San Francisco Bay have been conducted over the past several decades, but no synthesis of recent studies is available. The purpose of this report is to synthesize the best available data and knowledge to answer the following study questions:

- What are the magnitudes and sources of fine and coarse sediment transported to San Francisco Bay?
- What are the present temporal trends of fine and coarse sediment supply to San Francisco Bay?
- What are scenarios for future sediment supply to San Francisco Bay?
- How can sediment monitoring be improved to fill data gaps and better provide information for resource managers?

The primary audience for this report is state, federal, and regional agencies involved with sediment management issues. For example, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) has requested a synthesis of sediment data that would be useful for agencies involved with planning tidal marsh restoration, evaluating tidal marsh and mudflat resilience to sea level rise, planning dredging, designing coastal resilience, maintaining flood control channels, and regionally managing sediment. In addition, as a follow up to their October 2015 Regional Sediment Management Workshop, the San Francisco Bay Conservation and Development Commission (BCDC) asked the U. S. Geological Survey (USGS) for recommendations on which small tributaries should be monitored, how bed sediment load could be monitored, and how existing monitoring can be revised to better inform tidal marsh restoration projects. The management questions for this synthesis were crafted by the RMP Steering and Technical Review committees, which includes members from SFBRWQCB, U. S. Corps of Engineers, U. S. Environmental Protection Agency, and local dredgers. Information needs identified by BCDC as well as other agencies were also considered while crafting the questions for this report.

This synthesis report was prepared jointly by the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) and the USGS with funding from both organizations. The project is meant be a first step in the development of a more comprehensive sediment strategy for the Bay. The recommendations from this report will feed into the "*Healthy Watersheds- Resilient Baylands*" project. This future project will refine the recommendations for sediment supply monitoring and add recommendations for shoreline resilience monitoring to better inform tidal marsh restoration decision-making.

Summary of Recent Regional Scale Projects on Sediment Supply to the Bay

This report builds upon a large body of work on sediment supply to the San Francisco Bay-Delta. Several recent efforts that provide salient information for helping address questions related to present and future sediment load as well as sediment monitoring priorities are summarized below. As this was not intended to be an exhaustive review, there are many local scale projects that are not listed. Many of these may be relevant in the future once management priorities are refined.

- **Multi-decades of programs of monitoring and analysis -** San Francisco Bay is one of the most anthropogenically-impacted estuaries in the world (Nichols et al. 1986) and one of the most monitored and studied. Data spanning multiple decades and analyses of those data provide understanding of how humans affect sediment supply and San Francisco Bay. Notable contributors include the pioneering study of hydraulic mining effects by Gilbert (1917), mid-20th century studies (Porterfield 1980), and continuing tributary monitoring by the USGS and the RMP (http://www. sfei. org/rmp).
- A multi-discipline approach for understanding sediment transport and geomorphic evolution in an estuarine-coastal system: San Francisco Bay - This special issue of the scientific journal *Marine Geology* (Barnard et al. 2013) contains a series of manuscripts featuring state-of-the-art approaches to understanding the physical processes related to sediment transport and geomorphology of San Francisco Bay. The special issue has a comprehensive sand provenance study that includes a series of novel modeling techniques and data analyses to establish provenance and transport. The issue also describes efforts to understand fundamental sediment transport processes and circulation patterns at a range of spatial scales and within specific estuarine and adjacent environments, including: the exposed outer coast, tidal flats and marshes, the inlet, Bay tributaries, and the Bay floor.
- **Flood Control 2.0 -** Flood Control 2.0 ("FC 2.0", SFEI-ASC, 2016) was an EPA-funded project aimed at developing useful information for integrating habitat improvement and baylands resilience into flood risk management for channels at the Bay interface (floodcontrol.sfei.org). It included an assessment of contemporary average annual watershed sediment supply from the 33 largest watersheds draining to the Bay (extending the work on sediment loads presented by McKee et al. in the 2013 *Marine Geology* special issue). It developed new methods of estimating urban sediment supply; expanded the sediment database for a longer period of time; added bedload sediment transport data; and, collated the volume of sediment removed from fluvial and intertidal reaches over the past several decades to maintain flood conveyance capacity. In this USGS/RMP report, we build on the work from FC 2.0 to present the first regional

estimates of suspended load and bedload input to San Francisco Bay for an extended period (WYs 1995-2016) that take into account storage and removal processes in flood control channels.

- **Bayland Ecosystem Habitat Goals Science Update** - This multi-partner effort provided an update to the 1999 Baylands Ecosystem Goals project that accounted for the impacts of climate change and provided recommendations for achieving healthy resilient baylands (Goals Project, 2015, https://baylandsgoals. org/science-update-2016/). In particular, it set out a plan for attaining the goal of 100,000 acres of tidal marsh and identified shoreline areas where augmenting the current sediment supply will be essential for bayland survival into the future.
- **The Science of Sediment: Identifying Bay Sediment Science Priorities** - In October 2015, the Bay Conservation and Development Commission (BCDC) hosted a workshop to identify regional sediment science priorities (http://www.bcdc.ca.gov/cm/2016/0204Science-of- Sediment-Workshop-presentation. pdf). The ultimate goals of the workshop were to create a prioritized list of the most important sediment management questions for the Bay, and to develop a regional research strategy that would lay out a process for the studies and actions necessary to address these questions. The workshop summary report provides a discussion of the ideas generated at the workshop towards developing a regional sediment research strategy. One of the top ranked management questions from the workshop, "What do we estimate to be the change in sediment supply/erosion of our watersheds in the future (using modeling)?" is partially addressed in this USGS/RMP report.
- During the same period, BCDC published the **Central San Francisco Bay Regional Sediment Management Plan** (BCDC, 2016, http://www. bcdc. ca. gov/sediment/CentralSFBayRSMPlan. pdf). The plan is part of a larger coastal California Sediment Master Plan being coordinated by the Coastal Sediment Management Workgroup (CSWM), a collaborative task force of state, federal and local/regional entities concerned about adverse impacts of coastal erosion and excess sedimentation on coastal habitats. The Central San Francisco Bay Regional Sediment Management Plan focuses on improving the region's understanding of sediment transport and deposition dynamics within the Central Bay and recommend possible 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. The Plan identifies Bay- wide bathymetry and region-wide monitoring of suspended-sediment loads and bedloads in major tributaries draining to the Bay as critical data needs. This USGS/RMP report partially addresses the BCDC recommendations by updating the sediment supply estimates and outlining specific recommendations for improvements to the regional sediment monitoring design.

- **Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) -** This USGS project uses a model-based approach to develop a multi-decadal view of the San Francisco Bay/Delta estuary-watershed system (https://cascade. wr. usgs. gov). Simulations with linked models are used to project changes to discharge and sediment transport through and deposition dynamics within the Estuary under a range of plausible scenarios of climate change (which accounts for sea level rise and changes to surrounding watershed peak discharge magnitude) and changes to Delta land use.
- **DredgeFest California -** This effort began with a week-long event in June 2016 focused on investigating possible sediment futures for the San Francisco Bay/Delta and elucidating both the need for and possible supply of sediment for tidal wetland support. It resulted in an synthesis report with recommendations (Milligan et al. 2016) and an interactive online tool that allows users to see the amount of sediment that could be used for tidal wetland support from navigation dredging around the Bay and possible extraction from water supply reservoirs around the Bay Area (http://dredge3.s3-website- us-west-2.amazonaws.com/).

2. Methods

Sediment Supply from the Delta

Water and sediment draining from the Central Valley pass through the Delta and enter San Francisco Bay at the California Department of Water Resources (DWR) and USGS monitoring station at Mallard Island (Figure 2.1). DWR calculates daily tidally-averaged water discharge from the Delta to the Bay based on measured discharge data, estimated water use, evapotranspiration, and conservation of mass (http://www.water.ca.gov/dayflow/). Water discharge at Mallard Island is strongly affected by tides and is bidirectional. USGS began measuring suspended-sediment concentration (SSC) every 15 minutes at Mallard Island in 1994 (Buchanan and Morgan 2014). Using the available discharge and SSC data, McKee et al. (2006) developed a method to estimate the net daily quantity of suspended-sediment that passes Mallard Island. The method considers both the advective flux, the mass of suspended-sediment carried by the tidally-averaged discharge, and the dispersive flux which is created by the difference in SSC on flood and ebb tide. The estimated error of the method is +/- 32%. McKee et al. (2006) used the estimated daily flux to estimate fluxes for water years 1995-2003 and McKee et al. (2013) estimated WY 2004-2010. The water year begins October 1 and ends September 30 when both river discharges and SSC and thus flux are small, making the water year the preferred discretization to show annual variations and decadal trends. In the present report work, we extended the Mallard Island daily suspended-sediment flux estimates through WY 2016 using the previously published methods without modification (McKee et al., 2006).

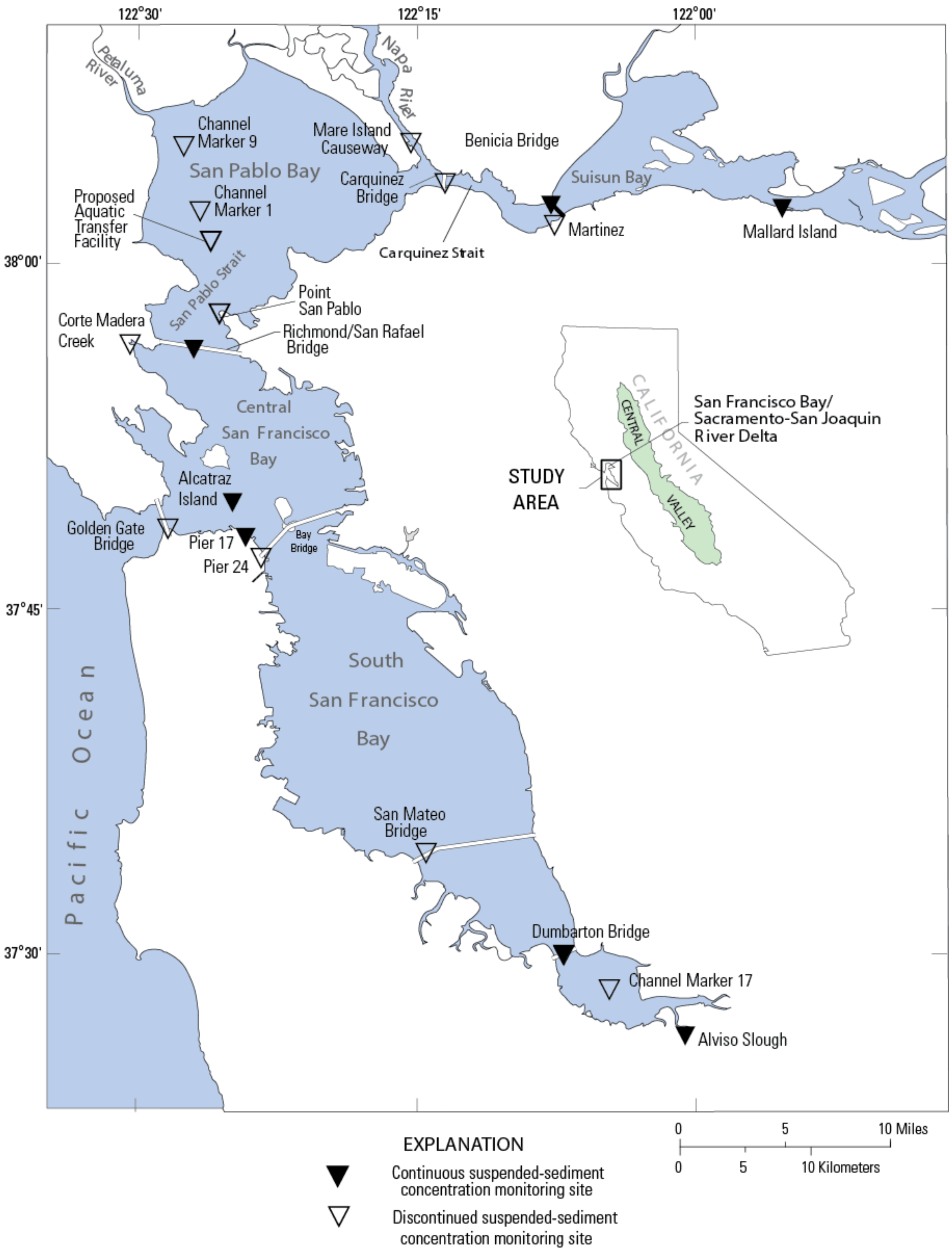


Figure 2.1. USGS suspended-sediment concentration monitoring stations in the Bay-Delta.

To evaluate past changes and current trends of suspended-sediment load, we used a double mass plot (see Figure 3.2 in the next section) which compares cumulative water discharge and cumulative sediment load to help remove the effect of interannual variability (Walling and Fang 2003, McKee et al.2013). The slope of the line is sediment load divided by water volume which is the mean SSC and has units of mass/volume. The slope can also be thought of as a sediment load (which is the mass of sediment supplied from the watershed) per unit area (mostly downstream from reservoirs) per unit of effective precipitation (which is the depth of precipitation that runs off the land). Thus, this method reduces the effects of climatic interannual variability by normalizing for discharge and effectively generating a visualization of discharge-weighted SSC.

To extend the double mass diagram back in time to before WY1995, monthly total suspended solids concentration (TSS) data collected by DWR (http://www.water.ca.gov/bdma/meta/Discrete/data. cfm) was used to construct a double mass diagram for water years 1976-2014. A disadvantage of this approach is that monthly data provides much less temporal resolution than the 15 minute data available beginning in WY1995. Data from station D4 in the lower Sacramento River were used because they have the longest duration closest to Mallard Island. Water year mean TSS values were calculated from the monthly data. In the Bay and Delta TSS and SSC are equivalent (Gray et al. 2000). Annual suspended-sediment load was estimated by multiplying the water year mean TSS by water year mean Delta freshwater discharge estimated by DWR (http://www.water.ca.gov/dayflow/output/).

We estimated the mean annual long-term sediment supply to San Francisco Bay at Mallard Island under current conditions by multiplying a representative SSC and water discharge. For SSC, we used the present slope of the Mallard Island double mass plot. For water discharge, we used the mean annual Delta outflow for WY 1981-2010 (22,800 Mm^3/yr). This 30-year period was chosen to be consistent with the current climate averaging period currently used by the Western Regional Climate Center (https://wrcc.dri.edu/) for rainfall data in California. It is also a long enough period to normalize sediment load variation across a nearly full range of climate (Inman and Jenkins, 1999) and it is short and recent enough to reflect the modern period of land and water management in the Central Valley.

Bedload is not currently measured at any streamgage in the Delta and there have not been any studies in which bedload measurements were collected in the Delta. A study by Porterfield (1980) provided estimates (calculated using indirect means) of bedload entering the Delta but not exiting the Delta. A later study by Dinehart (2002) calculated bedform transport rates using repeat bathymetry at the Garcia Bend reach in the Sacramento River. Both of these estimates were for the upstream areas of the Delta where about 1-2 percent of the sediment entering the Delta is thought to be transported as bedload (Porterfield, 1980; Marineau and Wright, 2014). Within the Delta, a large portion of sediment falls out of suspension in the Delta and becomes bedload or is deposited within the Delta (Wright and Schoellhamer 2005). Therefore, the estimate of bedload entering the Delta is not representative of that exiting the Delta. In the absence of bedload measurements, bedload exiting the Delta was estimated between 1997-2010 at 15-minute time steps using the van Rijn (1984) method at two USGS streamgages.

The input requirements for the van Rijn (1984) equations included: bed-material particle size, bedform dimensions, depth, and shear velocity. Bed-material particle size was measured from samples collected between 2010 and 2013 (Marineau and Wright, 2017). Bedform dimensions were measured in 2012 from several 100-130 m longitudinal depth profiles. A time series of average water depth was calculated based on channel cross-sectional area and stage (recorded at streamgages), and time series of shear velocity were calculated using the Keulegan (1938) equation, which relates depth-averaged water velocity to shear velocity by assuming a logarithmic velocity profile. While bed-material particle sizes at each site did not change substantially from year to year and channel cross-sectional area generally does not change in the Delta, bedforms were only measured one time and their dimensions were assumed static for the period of study (1997-2010). However, bedforms in fluvial environments can often change with increasing or decreasing discharge (for example, Julien and Klassen, 1995; Dinehart, 2002). Bedload estimates were made at two streamgages: Sacramento River at Rio Vista (SRV), and San Joaquin River at Jersey Point (SJJ), both located 25 km upstream of Mallard Island (Figure 2.2). Bedload at Mallard Island is estimated by two methods: 1) assuming Mallard Island bedload is the same as the sum of bedload at the two upstream gages and 2) subtracting the quantity of sediment removed by dredging and sand mining in the 25 km tidal reach from the sum of bedload at the two upstream gages.

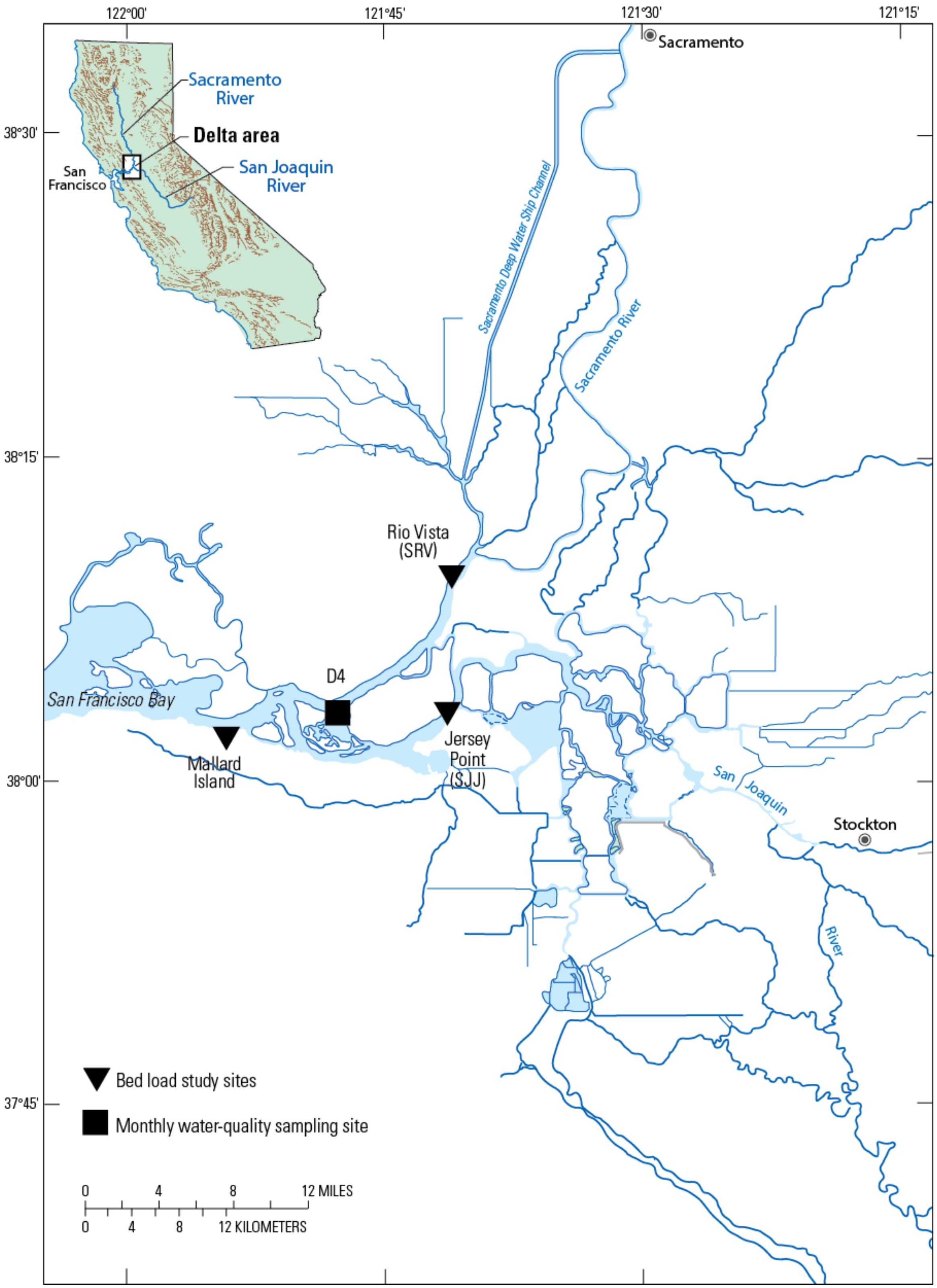


Figure 2.2. Monitoring locations used for bedload computations.

Sediment Supply from Bay Area Watersheds

History of Information Development

Estimates of suspended-sediment supply from small tributaries that enter the Bay from the counties around the Bay (Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo and San Francisco) have been made periodically (Krone, 1979; Porterfield, 1980; Davis et al., 2000; McKee et al., 2003; Lewicki and McKee, 2010; McKee et al., 2013; SFEI-ASC, 2016). Initially, data were available for relatively few tributaries and for short periods of time necessitating broad general assumptions about representativeness but allowing for a general idea of annual average loads to be generated, with lesser confidence for bedloads (Krone, 1979; Porterfield, 1980) or with no bedload estimates at all (Davis et al., 2000; McKee et al., 2003; Lewicki and McKee, 2010; McKee et al., 2013). It is also important to note the climatic decoupling between the Central Valley watershed, which is influenced by rainfall and snow accumulations, and the coastal watershed, which is mainly influenced by Pacific storm rainfall alone. Knowing these challenges, McKee et al. (2013) collated a much larger (38 locations) and longer term suspended-sediment data set (1957-2010) to make regional estimates of loads for 16 years (WY 1995-2010) based on a total of 235 station-years of data.

Although deemed a reasonably accurate estimate of suspended-sediment load on a regional basis for select well-sampled tributaries, McKee et al. (2013) recognized a major weakness was the remaining lack of information on bedload. They commented on the relative lack of bedload data (at that time thought to be 40 station years across just 10 locations), and identified the need to do a more thorough data search. These authors also recommended that computations of bedload supply to the Bay would need to take into account storage and removal processes in actively managed flood control channels. Due to a lack of local urban runoff sediment load data at that time and no agreed upon impervious cover layer to define urban and non-urban land use, another weakness in the work of McKee et al. (2013) was the use of a land use-based method to estimate suspended-sediment loads in ungaged watersheds. The method they adopted applied erosion rates not specific to the Bay Area (i.e., from the EPA BASINS manual, https://www.epa.gov/exposure- assessment-models/basins-user-information-and-guidance, and US Dept. of Agriculture) and adjusted these by a delivery ratio.

These weaknesses were addressed through further methods development and data collation during the Flood Control 2.0 project (SFEI-ASC, 2016) for a select group of 33 flood control channels using local urban runoff suspended-sediment loads data (rather than using nationally developed EPA/USDA empirical land use relations), impervious surface data, and by taking into account storage and removal processes in channels where data were available. However, no new regional estimates were made at that time.

In this report, we present the first ever regional estimates of suspended load and bedload input to San Francisco Bay for an extended period (WYs 1995-2016) that take into account storage and removal processes in the fluvial portions of flood control channels. Sediment processes that include net trapping and dredging in tidal portions of channels are not addressed in this report. For the purposes of this synthesis, once the sediment has passed downstream from the head of tide point in the channel, the sediment is deemed to have "arrived in the Bay".

Sediment Load Computation Methods

The methods employed during this synthesis have been previously developed and described in detail (McKee et al., 2013; SFEI-ASC, 2016). Here the methods are described with only enough detail to provide context for review and critique of the results and to help provide context for some of the recommendations.

Estimates of Watershed Boundaries and Characteristics

A geographic information system (GIS) was used to compile data and develop information on watershed boundaries and characteristics. Two primary watershed boundary data sets were used. For tributaries draining to the Bay from Contra Costa, Alameda, Santa Clara, and San Mateo counties, and the non-combined sewer area of San Francisco county, we used the watershed boundary layer developed by the RMP Sources Pathways and Loadings Workgroup and which is used to support the regional watershed spreadsheet model (RWSM) (Wu et al., 2017). For the North Bay tributaries draining the counties of Marin, Sonoma, Napa, and Solano, we used a watershed boundary layer developed in 2008 for previous suspended-sediment loads estimates (Lewicki and McKee, 2010; McKee et al., 2013). The only major adjustment made to these layers was to the "exit location" (or "pour point") to the Bay defined as the head of tide or the place in the landscape where fluvial processes transition to tidal processes. Originally, the edge of the historical Bayland was used as the upper limit of tide for small tributaries. However, the improved position of head of tide (HOT) that was developed during the FC 2.0 project for major flood control channels (based on a combination of manager knowledge, vegetation indicators, and NOAA Sea-Level Rise Viewer, https://coast.noaa.gov/digitalcoast/tools/slr) was adopted here. The resulting data set was then combined with point data on gaging locations and the locations of major reservoirs (http://www.water.ca.gov/damsafety/damlisting/index. cfm) (those that impound water from catchment areas >50 km^2), and impervious cover from the national land cover database (NLCD; https://www.mrlc.gov/nlcd2011. php, Homer et al., 2015). This was used to generate information of watershed area and percent imperviousness for three locations within each watershed (area upstream from HOT, area upstream from the most downstream gauging location, and area upstream from the most downstream reservoir). These were the basic geographic data used for the sediment loads computations.

As mentioned above, sediment that passed downstream from head of tide is deemed to have arrived in the Bay. However, trapping is known to occur in the intervening tidal channels downstream from the head of tide but upstream from the open Bay. In the Bay Area, these tidal channels and the lower part of the fluvial channel upstream are often included in the flood control channel network that is managed by various county and flood control agencies because they convey flood waters through low-lying urban areas to the Bay. An example of this tidal channel trapping process is provided by Downing-Kunz and Schoellhamer (2015) who compared sediment flux measured at the mouth of Corte Madera Creek to sediment load measured just above the head of tides. During wet periods, they found that net suspended-sediment flux at the mouth was seaward. For individual storms the fraction of sediment trapped in the flood control channel decreased as the peak discharge increased and the largest storms caused net erosion. During dry periods, net sediment flux at the mouth was landward indicating sediment from the Bay moved into the Creek (Downing-Kunz and Schoellhamer 2013). The Corte Madera flood control channel acted as a sediment sink that trapped sediment entering from the watershed and some sediment entering from the Bay. Overall about half of the sediment that entered the flood channel from the watershed was trapped and deposited in the tidal portion of the flood channel over the 3-year study period (Downing-Kunz and Schoellhamer 2015). Similar trapping of Bay sediment has also been observed in Mare Island Strait (Warner et al., 2002), the Napa and Sonoma Baylands (Warner et al., 2003), the Petaluma River channel (Ganju et al., 2004), and the Alviso Slough (Shellenbarger et al. 2015). Although these depositional processes have been studied and flood control agencies are actively managing and removing this sediment, these processes are not considered in the estimates provided here for net sediment supply to the Bay. Functionally here, the Bay defined as everywhere in a channel or wetland that is downstream from head of tide in all the hundreds of small tributaries and small urban outfalls that ring the Bay.

Estimates of Peak Discharge

Peak discharge data for Bay Area gaging locations operational between WY 1995 and 2016 were downloaded from the USGS website (https://nwis.waterdata.usgs.gov/ca/nwis/sw). When appropriate, these data were used directly for sediment computations in watersheds and for time periods where there were data available. For all other watersheds or time periods, a series of 22 WY specific regression relations were developed for WYs 1995-2016 to estimate peak discharge based on the unimpounded area upstream from each gage following the methods of McKee et al. (2013). To do this, the region was subdivided into three hydrogeomorphic provinces defined by climate and geology (East Bay: Contra Costa and Alameda Counties, North Bay: Marin, Sonoma, Napa, and Solano Counties, and San Francisco Peninsula/South Bay: San Francisco, San Mateo, and Santa Clara Counties) based on based on previous work of Rantz (1974), and the recommendations of Lewicki and McKee (2010). This led to a significant improvement in correlation between the area of a watershed and the annual peak discharge and subsequently, peak discharge and suspended load (Lewicki and McKee, 2010; McKee et al., 2013). For the East Bay sub-region regression, 7-10 gages were used with 7 used for WY 1995 and 1996. For the North Bay, 5-9 gages were used with 5 used during WYs 1998, 1999, and 2000. For the Peninsula/ South Bay sub-region regression, 4-8 gages were available; the WYs with 4 used were WYs 1995-2002 inclusively. A power function was used to relate area and peak discharge within each province. The strongest relations were found for the East Bay with correlation coefficients ranging between 0.78-0.89 ($p<0.002$). The worst, but still acceptable relations, were for the North Bay with correlation coefficients ranging between 0.57-0.97 ($p<0.05$). Overall, the median and mean r^2 for all the data were 0.88 and 0.85.

Estimates of Suspended-sediment Load

The suspended-sediment loads database was updated building from the most recent collation that included data up to WY 2013 (SFEI-ASC, 2016). The database used in this report includes all known data for the Bay Area through to WY 2016. The majority of data were downloaded from the USGS website (https://nwis.waterdata.usgs.gov/ca/nwis/sw).

Suspended-sediment records began in the Bay Area in Sonoma Creek (1956), Alameda Creek and Guadalupe River (1957), and Coyote Creek and San Francisquito Creek (1962) (Figure 2.3). Since that time, monitoring for suspended sediment has occurred in 37 tributary locations for a total of 276 station years.

The watersheds draining the Bay Area were organized into three groups. The first group of watersheds (mostly a subset of the watershed channels that were considered in the FC 2.0 project (SFEI-ASC, 2016)) is a series of 13 well-sampled mixed land use watersheds that drain to the Bay[1] that collectively represent an area of 4,763 km^2 (59% of the land area of interest). For this set, watershed specific regressions were developed. These were based on relating empirical discharge to empirical suspended-sediment load data using a power function to estimate suspended-sediment loads for unmeasured years following published methods (McKee et al., 2013; SFEI-ASC, 2016). We have the greatest confidence in the suspended-sediment load estimates from these watersheds collectively. The average error for this group of watersheds was estimated to be +/- 25% by McKee et al., 2013; since the methods used here were identical, this estimate of error remains valid.

[1] Corte Madera Creek, Sonoma Creek, Napa River, Walnut Creek, San Leandro Creek, San Lorenzo Creek, Zone 4 Line A in Hayward (Not included in FC 2.0), Alameda Creek, Zone 6 Line B in Fremont (Not included in FC 2.0), Coyote Creek, Guadalupe River, Sunnyvale East Channel, and San Francisquito Creek

For the second group of watersheds comprising 2,330 km^2 (29% of the land area draining from the nine counties around the Bay), neither discharge nor suspended-load data were available. For this group suspended-sediment loads were estimated separately for the urban and non-urban portions (defined by impervious cover). For non-urban ("pervious") areas of the watersheds, sediment loads estimates were made by combining peak discharge data, estimated using the appropriate sub-regional WY specific area-discharge regression relations (see the peak discharge estimates section above), with suspended-sediment load derived using the appropriate sub-regional peak discharge-suspended-sediment load regression equations (Figure 2.4). Estimates of annual suspended-sediment load for urban areas were based on the best available Bay Area empirical field measurements (Zone 4 Line A in Hayward, CA: 31.5 t/km^2 (McKee and Gilbreath, 2015) and the urban portion of Guadalupe River: 51 t/km^2 (McKee et al., 2017)). Here we used an average of the two published numbers (41.25 t/km^2 equivalent to 118 $tons/mi^2$). The resulting average annual loads for impervious areas were then adjusted for the 22 year period using linear scaling and a representative discharge gage for the North Bay (Napa River near Napa), the East Bay (San Lorenzo Creek at San Lorenzo), and the Peninsula/South Bay (Matadero Creek at Palo Alto) so that an average of 118 $tons/mi^2$ over 22 years was conserved. The two estimates (the one for non-urban areas and the other for urban areas were then summed for each of the 22 years. McKee et al. (2013) carried out a detailed error analysis for this group of watersheds based on the methods they applied at that time and estimated an error to be +/- 51%. Given that the methods have now been improved by the use of locally measured urban suspended-sediment loads, this estimate of error is now considered conservative.

For a third group of watersheds (the remainder of those considered in the FC 2.0 project)[2] that together comprised another 952 km^2 (12% of the land area of interest), the methods developed in the FC 2.0 project were followed by extending the load analysis for another three years through WY 2016. The methods followed were watershed-specific and tailored to maximize the use of available data to generate the best estimate of loads. The methods involved a combination of local and sub-regional regression relations to estimate discharge, suspended-sediment, and bed loads (see SFEI-ASC, 2016 for details on the narrative method followed for each watershed). The errors associated with this group of watersheds are deemed to be intermediate between the other two groups (+/- 40%).

[2] Matadero Creek, Novato Creek, Old Alameda Creek, San Pablo Creek, Alhambra Creek, Pinole Creek, Rodeo Creek, Wildcat Creek, Lion Creek, Lower Penitencia Creek, San Tomas, Stevens Creek, Calabazas Creek, Permanente Creek, Colma Creek, Adobe Creek, San Bruno Creek, Belmont Creek, Sunnyvale West Channel, Petaluma River, and Coyote Creek Marin

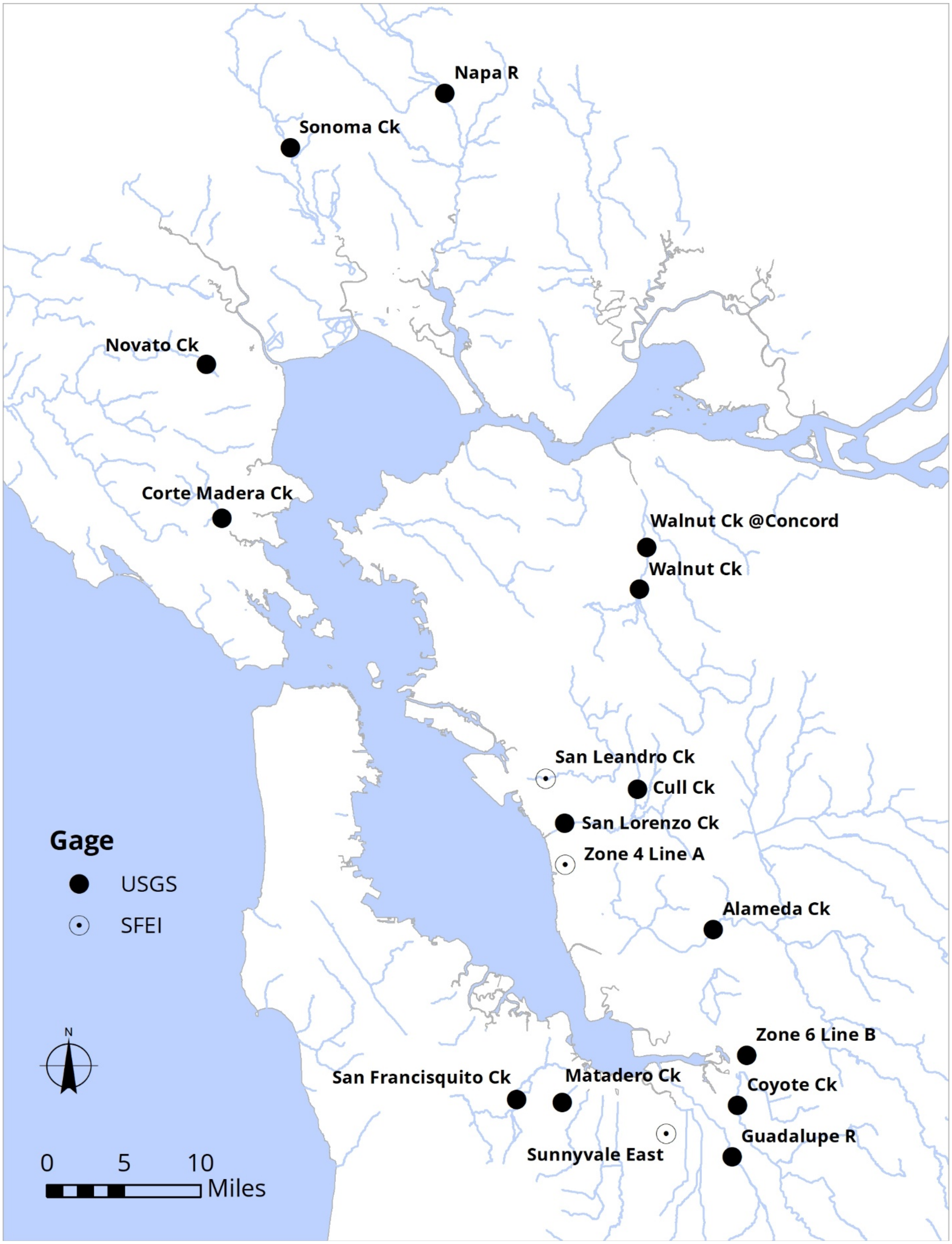
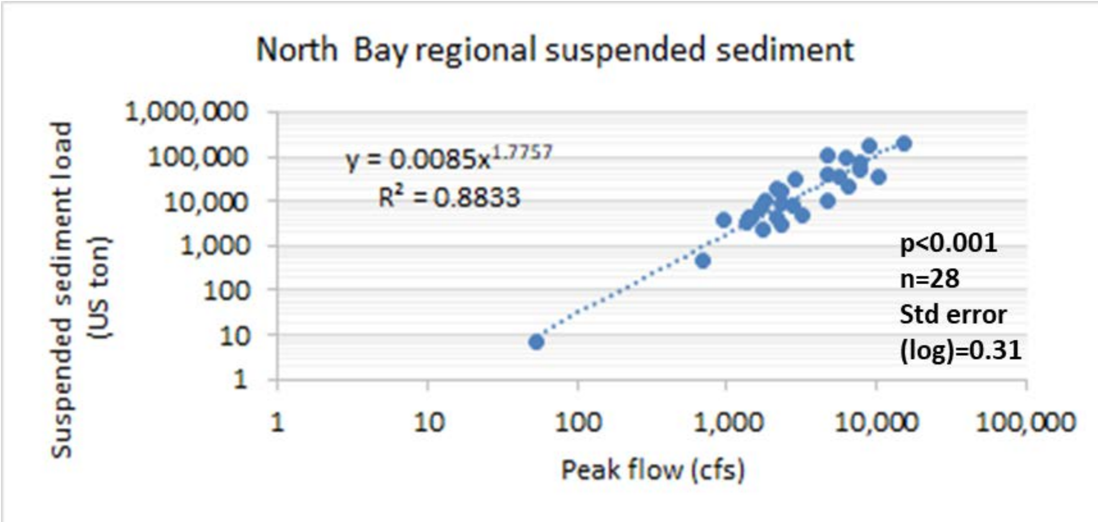
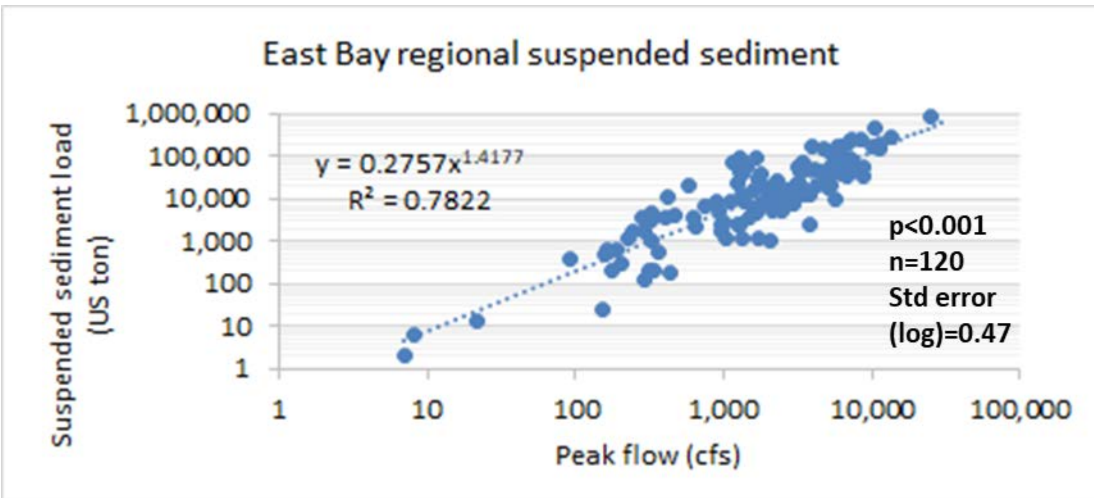


Figure 2.3. USGS stream gages in the San Francisco Bay Watershed.





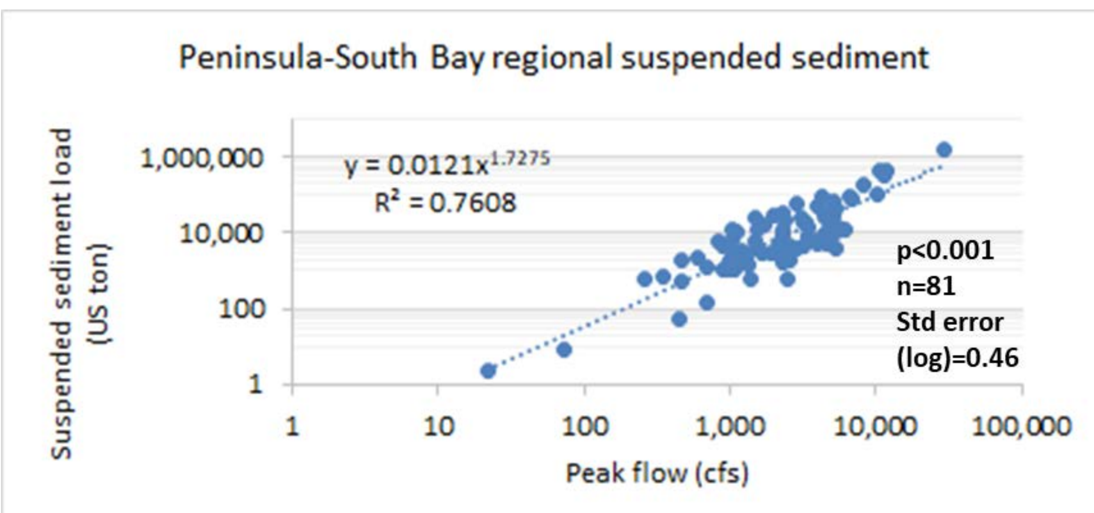


Figure 2.4. Sub-regional regression relations between peak discharge and suspended-sediment loads.

Estimates of Bed Sediment Load

The bedload database compiled as part of FC 2.0 was extended to WY 2016. The majority of the new data were downloaded from the USGS website (https://nwis.waterdata.usgs.gov/ca/nwis/sw). Based on this effort, we know of 15 locations in the Bay Area with bedload measurements for a total of 106 station years. Published bedload sediment records began in the Bay Area much later that suspended-sediment load records mainly due to the later invention and standardization of bedload sampling methods (the "Helley-Smith sampler") and probably due to the flashy nature of creeks and the overall greater difficulty in deploying the equipment. Early measurements were made in Calabazas Creek (WY 1973) but reported as total load. Then, measurements began in a number of creeks by the late 70s and early 80s (Wildcat: WY 1977; Napa River and Corte Madera Creek: WY 1978; Cull Creek: WY 1979; San Lorenzo Creek: WY 1981). The longest records of bedload measurements occurred in the East Bay (Cull Creek above Cull Creek Reservoir near Castro Valley: 23 years; San Lorenzo Creek above Don Castro Reservoir near Castro Valley: 19 years; Alameda Creek at Niles: 15 years; Alameda Creek below Welsh Creek near Sunol: 11 years) (See Table 6.1 in the Appendix). Together these locations account for 68 of 86 station years of measurements in the East Bay and the majority of the 106 station years currently known about in the Bay Area. Our regional bedload estimates are based upon these data.

Bed sediment loads were estimated for seven mixed land use watersheds that drain to the Bay (Corte Madera Creek, Napa River, Walnut Creek, San Lorenzo Creek, Alameda Creek, Zone 6 Line B, and Guadalupe River) using field collected empirical watershed specific data. These watersheds collectively represent an area of 3,354 km^2 (42% of the land area of interest). Watershed specific power function regressions relating all available empirical discharge to empirical bedload data were used to estimate bed sediment loads for unmeasured years based on published methods (SFEI-ASC, 2016). For these watersheds, the total error was estimated as the square root of the sum of the squares of the individual errors, assuming that all errors are random and uncorrelated. Sources of uncertainty include:

1) the measurement of instantaneous peak discharge by the USGS using the area velocity method and a rating curve (+/-10%),
2) the laboratory analysis of bedload samples collected by the USGS (+/-15%),
3) the use of rating relations between instantaneous discharge and bedload by the USGS to compute bed sediment loads (+/-40%), and,
4) the use of a regression estimator between instantaneous peak discharge and annual bedload to estimate loads for unmeasured years. In this case we used the area weighted mean of the correlation coefficients (r^2) of the regression equations (+/- 27%) by assuming that the error was +/-50% for any watershed with three or less years of data.

The resulting total error was the square root of the sum of all the error terms squared or +/-52%.

For the non-urban portions of all other watersheds (the remaining 58.3% of the drainage area of interest), bedloads were estimated for each water year by combining peak discharge data estimated using the appropriate sub-regional WY specific area-discharge regression relations with the appropriate sub-regional peak discharge-bed sediment load regression equations. The East Bay bedload equation was developed with data from seven stations (three in Alameda Creek watershed, three in San Lorenzo Creek watershed and Wildcat Creek) for a total of 60 station years. Data availability was worse for the Peninsula/ South Bay regression (15 station years from three watersheds) and the North Bay regression (three station years from two watersheds: Corte Madera and Napa). This lack of data is discussed later in this report. The total error associated with applying this method was computed using the following sources of uncertainty:

(1) the measurement of instantaneous peak discharge by the USGS using the area velocity method and a rating curve (+/-10%);

(2) discharge estimation using WY specific area-peak discharge regressions (here we adopted the mean for the region (+/-7.5%);

(3) the laboratory analysis of bedload samples collected by the USGS (+/-15%);

(4) the use of rating relations between instantaneous discharge and bedloads by the USGS to compute bed sediment loads (+/-40%), and

(5) the use of a regression estimator between instantaneous peak discharge and annual bedload for each province (since there are large differences in the geology and land use between sampled and unsampled watersheds leading to unknown and large extrapolation errors, we adopted a conservative error estimate for this term of +/-50%).

The resulting total error was the square root of the sum of all the error terms squared or +/-67%.

Impervious urban areas were assumed to produce no bedload, within the accuracy of the measurements. Although there are no local data to support this assumption, urban systems are engineered and managed to reduce the frequency of landslides, earth flows, and bed and bank erosion (all processes that supply bedload materials for transport). We acknowledge that this is not true during rapid urban development phases where changes in runoff characteristics can induce incision and hydromodification (as likely indicated for example by the WYs 1957-1962 in Guadalupe River, the WYs 1966-1970 data in Colma Creek and the Spruce Branch Tributary to Colma Creek, and the WYs 2000-2002 data on Zone 6 line B). However, in most built out urban areas of the Bay Area, sediment loads have likely reached an equilibrium phase with insignificant amounts of bedload transport relative to suspended-sediment transport.

Estimates of Sediment Stored or Removed from Flood Control Channels

As mentioned earlier, an improvement in this report, compared with all earlier estimates of sediment supply to the Bay, was to include estimates of sediment stored in, or removed from, flood control channels. Details on the methods and data were reported through the FC 2.0 project

(SFEI-ASC, 2016). The methods are outlined here briefly to provide context for review and to support recommendations that are presented near the end of this report. Data on sediment removal quantities, location, dates, and in channel deposition were obtained by reviewing reports prepared by flood control, city, and county agencies and their consultants and by conducting interviews with agency staff. Data from these various sources was combined so that a chronology of sediment removal and deposition was developed and then quality checked. Data were obtained for Coyote Creek (Marin), Corte Madera, Novato Creek, Napa River, Walnut Creek, Alhambra Creek, Pinole Creek, Rodeo Creek, Wildcat Creek, Lion Creek, San Leandro Creek, San Lorenzo Creek, Old Alameda Creek, Alameda Creek, Lower Penitencia Creek, Coyote Creek (Santa Clara), Guadalupe River, San Tomas Creek, Matadero Creek, Stevens Creek, Calabazas Creek, Permanente Creek, San Francisquito Creek, Colma Creek, Adobe Creek, San Bruno Creek, and Belmont Creek. Although the data base contains information for both fluvial and intertidal reaches, here only fluvial data were used for the period WY 1995 to present. Thus, these estimates are for sediment supply to the head of tides and do not consider sediment trapping in the tidal channel between the head of tides and the larger Bay (remember, for the purposes of this synthesis, we consider the Bay to be everywhere downstream from the head of tide in each of the fluvial channels). For Corte Madera Creek, Downing-Kunz and Schoellhamer (2015) found that about one-half of the sediment supply from the watershed was trapped in the tidal channel.

Data for removal were only collated to WY 2013; further effort would be needed to add data for WY 2014-2016 but this is beyond the currently available resources. Data were most weak for deposition rates, therefore a variety of methods were used to estimate the volume of sediment that has been deposited in creeks. We used any existing data from FC 2.0 first, as it was deemed to be most reliable. To extend the data further, deposition rates based upon previous removals were calculated and used to project the deposition rates forward. Then any specific project-based knowledge about a creek, including personal observation by the project team, was also used.

Volumes for both deposition and removal were obtained in units of cubic yards, but load is measured and calculated as mass in units of tonnes. To convert sediment volume to sediment mass, we used a conversion factor of 1 cubic yard of bedload = 1.27 tonnes of bedload. Note, this conversion factor was based on data and observations made in San Francisquito Creek and Walnut Creek and used as representative of the small tributaries (SFEI-ASC, 2016) and differs from the factor we used for conversion of volume to mass for the Delta sediment loads (1 cubic yard = 0.65 tonnes (Porterfield, 1980). Conversion factors vary based upon the type of sediment involved; fluvial sediment is generally coarser (sand and gravel) which increases bulk density. In addition the minerals comprising fluvial sediment are more dense compared to the silt and clay of Bay sediment.

Sediment Transport Between Subembayments

With the present monitoring design, it is possible to measure the sediment flux into and out of two of the five subembayments in San Francisco Bay. Measurements at the Dumbarton Bridge monitor sediment transport between Lower South Bay and the rest of the Bay. Similarly, measurements at the Benicia Bridge are used to track transport between Suisun Bay and the rest of the Bay. San Pablo Bay, Central Bay, and South Bay are the other three subembayments.

Sediment transport into and out of these subembayments is not currently monitored.

Dumbarton Bridge

Sediment supplied by tributaries south of the Dumbarton Bridge enters Lower South San Francisco Bay which is a sink for suspended-sediment. The USGS uses continuous measurements of turbidity, water velocity, and water level and discrete measurements of cross sectional water discharge and suspended-sediment concentration to calculate a time series of suspended-sediment flux in kg/sec past the Bridge (Shellenbarger et al. 2013). Livsey et al. (in review) developed a correction for tidal asymmetry of the size of suspended flocs of sediment that affects the relation between turbidity and suspended-sediment concentration. On flood tide, suspended-sediment is sometimes more flocculated, resulting in less turbidity per unit mass of suspended-sediment and faster settling particles. Optical measurements of turbidity underestimate SSC and thus flood (landward) suspended-sediment flux is underestimated. The difference between mid- depth and near-bottom turbidity sensors increases during flood tide because the settling velocity is greater. This difference is used as a surrogate for particle size to correct the flux data.

Benicia Bridge

Suspended-sediment flux at the Benicia Bridge for water years 2002-2016 were estimated with surrogate relations dependent on Delta outflow, SSC, and the longitudinal salinity difference across Suisun Bay (ΔS). The Benicia Bridge is at the seaward boundary of Suisun Bay.

Suspended-sediment flux at Benicia and Mallard Island which is at the landward boundary of Suisun Bay can be combined to estimate the sediment budget for Suisun Bay because they are the major sources and sink for sediment entering or leaving Suisun Bay.

Ganju and Schoellhamer (2006) used detailed measurements of suspended-sediment flux to develop relations for different components of flux based on continuously measured quantities. Advective flux includes river discharge and is a function of the product of tidally-averaged discharge and SSC. Dispersive flux is the tidally-averaged flux that results from tidal asymmetry of discharge and SSC which is often affected by gravitational circulation and is a function of tidally-averaged discharge, ΔS at the water surface, and the tidal cycle variability of SSC. Stokes drift is the tidally-averaged flux that results from tidal asymmetry of discharge and water level, and is a function of SSC. Details are available from Ganju and Schoellhamer (2006) and the estimated error of the method is +/- 44%.

We estimated the mean annual long-term deposition rate of Suisun Bay under current conditions by regressing water year deposition with Delta outflow and assuming that mean annual Delta outflow for WY 1981-2010 (22,800 Mm^3/yr) is representative of the average current conditions. This method is similar to our approach for estimating mean annual long term suspended-sediment load at Mallard Island.

3. Results

Sediment Supply from the Delta

Suspended-sediment Loads from the Delta

Suspended-sediment load at Mallard Island from WY 1995 through WY 2016 has varied by 27-fold between years due to variability of rainfall and snow accumulations and snow melt (Table 3.1, Figure 3.1). The discharge-weighted mean (DWM) SSC is the discharge-normalized load which equals load divided by discharge. DWM SSC varies by just 3.2-fold indicating that discharge variability is the main driver for load variability. Variable precipitation and discharge act as noise that masks the sediment load of the Central Valley and trends in sediment supply.

Mean yield (the load normalized for the drainage area) was computed assuming the source area for eroded sediment is only the area downstream from the major Central Valley dams (80,080 km^2). The yield computed this way is estimated to be 9.1 (t/km^2), relatively low compared to yield computed for the smaller tributaries around the Bay (see Table 3.5 on page 34 for details).

Table 3.1. Total annual discharge, suspended-sediment load, and mean suspended-sediment concentration (SSC, equal to load divided by discharge) at Mallard Island for water years 1995-2016.

Water Year	Total Annual Discharge (Mm^3)	Suspended-Sediment Load (Mt)	Discharge-Weighted Mean Annual SSC (mg/L)
1995	51,559	2.58	50
1996	31,448	1.01	32
1997	42,350	2.24	53
1998	53,026	2.38	45
1999	27,799	0.84	30
2000	22,427	0.66	29
2001	8,604	0.26	31
2002	11,343	0.31	27
2003	17,356	0.55	32
2004	18,610	0.64	34
2005	19,046	0.43	23
2006	51,254	1.41	28
2007	7,643	0.12	16
2008	8,312	0.22	26
2009	8,443	0.16	19
2010	12,539	0.31	25
2011	33,235	0.60	18
2012	9,940	0.19	19
2013	11,299	0.29	26
2014	5,290	0.10	18
2015	7,687	0.19	25
2016	14,048	0.50	36
Total	**473,257**	**16.0**	**-**
Minimum	5,290	0.10	16
Maximum	53,026	2.6	53
Variation	10	27	3.2
Mean Annual	21,512	0.73	34

(a)

(b)

(c)

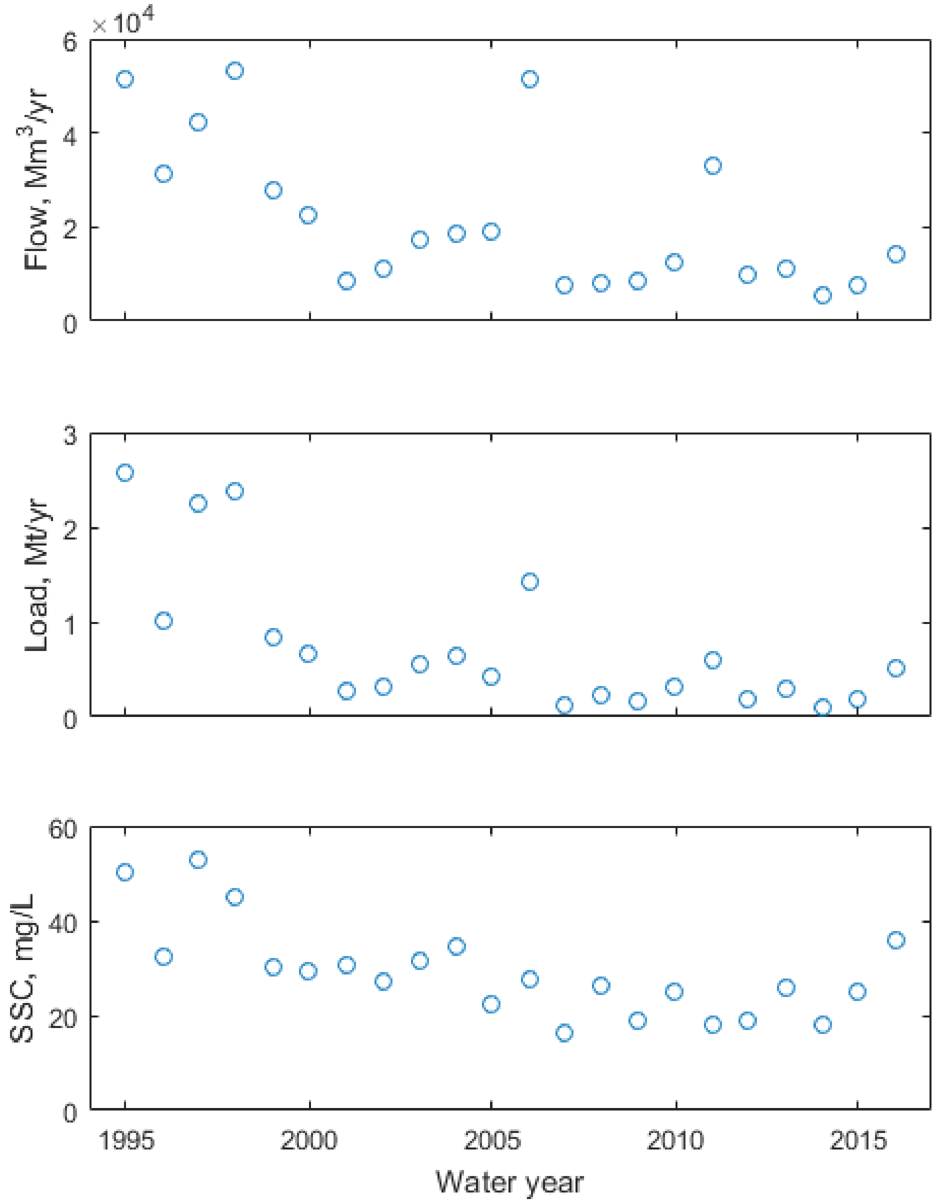


Figure 3.1. Total annual discharge, suspended-sediment load, and mean suspended-sediment concentration (SSC) at Mallard Island for water years 1995-2016.

Figure 3.2 is an update of the double mass plot for Mallard Island first presented by McKee et al. (2013). The double mass diagram has 2 linear segments with the slope of the WY 1999-2016 line being 45% less than the slope of the WY 1995-1998 line. This is caused by the step decrease in SSC throughout San Francisco Bay in water year 1999 (Schoellhamer, 2011). The two segments are linear because the SSC change was a fairly sudden step decrease (Figure 3.1, Table 3.1).

Collection of continuous SSC data at Mallard Island started in 1994, so there are fewer annualized data prior to WY 1999 than after. Monthly data collected by the USGS *RV Polaris* in San Francisco Bay corroborates the step decrease in WY 1999 after large discharges caused by El Niño conditions exported sediment and Bay sediment transport changed from transport- to supply- limitation (Schoellhamer 2011). This is similar to the changes seen downstream from new dams that suddenly reduce the sediment supply in a river (Walling and Fang 2003).

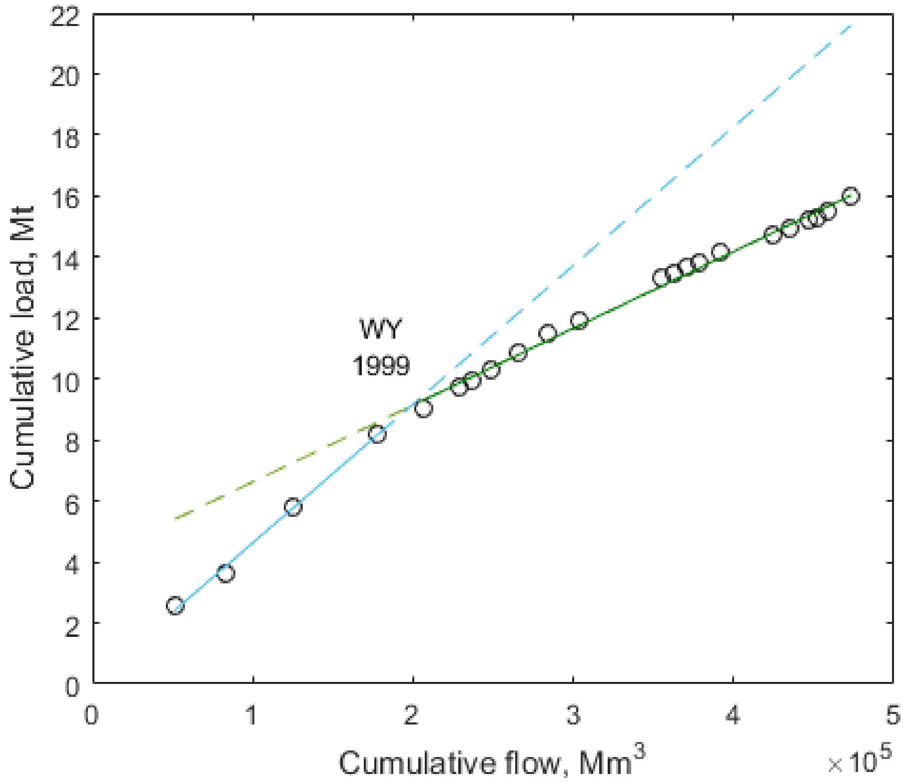


Figure 3.2. Double mass diagram for Mallard Island, water years 1995-2016. The blue line is a linearly regressed line to the WY 1995-1998 data and the green line is a linearly regressed line to the WY 1999-2016 data. The different slopes for the two regression lines are associated with the step decrease in SSC in San Francisco Bay in WY 1999.

Table 3.2. Statistical comparison of lines fit to segments of the WY 1995-2016 double mass diagram from continuous data at Mallard Island (Figure 3.2).

Water Years	**1995-1998**	**1999-2016**
Slope (mg/L)	45.5	25.2
r^2	0.995	0.994

The WY 1999-2016 line on the double mass diagram is the best available representation of present suspended-sediment supply from the Central Valley to San Francisco Bay. During WY 1999-2016, the mean discharge was 16,400 Mm^3/yr, the mean suspended-sediment load was 0.433 Mt/yr, and the mean SSC was 25.2 mg/L.

The double mass diagram for WY 1976-2014 (Figure 3.3) is less smooth than the one constructed from continuous data (Figure 3.2) because only about twelve TSS samples are available per water year but it confirms previously discussed concepts. The diagram has three linear segments (Table 3.3). In WY 1983 the slope decreased 47% following high discharges during an El Niño year that caused a step decrease in SSC (Hestir et al. 2013). The change in slope for the double mass plots during high discharge years is because high discharges mobilize more sediment than low discharges and the relationship is non-linear. From 1983 to 1997 the slope of the diagram is constant which indicates constant load, validating the constant sediment supply for WY 1995-1998 in Figure 3.2. After WY 1998 the slope decreases 33% due to another El Niño year and step decrease in SSC. The slope break occurs one year earlier with the monthly data and there is a visual break in the curve because twelve samples are less representative of the water year than continuous data. The data forming the regression slope after WY 1998 shows little scatter, indicating relatively constant sediment supply per unit of water discharge.

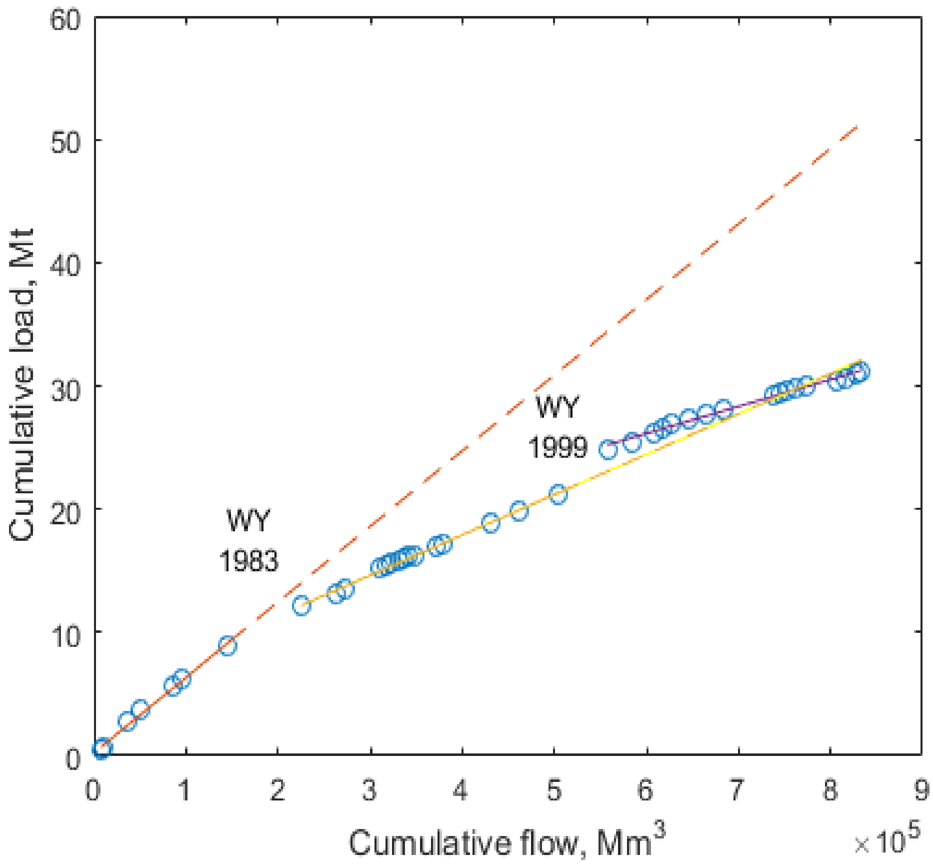


Figure 3.3. Double mass diagram for the lower Sacramento River 9 km upstream from Mallard Island, water years 1976-2014. Monthly TSS data are from DWR (http://www.water.ca.gov/bdma/meta/Discrete/data. cfm) station D4 in the lower Sacramento River. The brown line is a linearly regressed line to the WY 1976-1982 data, the yellow line is a linearly regressed line to the WY 1983-1997 data, and the purple line is a linearly regressed line to the WY 1998-2014 data. Step decreases in TSS in WY 1983 and WY 1999 cause the breaks in slope.

Table 3.3. Statistical comparison of lines fit to segments of the WY 1976-2014 double mass diagram from monthly data in the lower Sacramento River (Figure 3.3).

Water years	**1976-1982**	**1983-1997**	**1998-2014**
Slope (mg/L)	61.3	32.7	21.9
r^2	0.992	0.995	0.987

Sediment Bedload from the Delta

For the period WY 1997-WY 2010, mean bedload moving seaward at Rio Vista and Jersey Point 25 km upstream from Mallard Island was estimated at 51,400 ± 8,700 m^3/yr or 0.0775 ± 0.0131 Mt/yr using a conversion factor of 1,507 kg/m^3 (based on methods by Lara and Premberton (1963) and bed-material sizes published in Marineau and Wright, 2017). Table 3.4 provides summary results for each water year between 1997 and 2010. The bedload was about 7% of the total sediment load (based on these estimates of bedload and USGS measurements of suspended load at the two gages). Total bedload quantities varied somewhat from year to year, but the greatest bedload transports occurred in water years 1998 and 2006 in which large volumes of water discharged through the Delta. During these two years, about 0.173 Mt/yr of bedload moved seaward, while during all other years, the average was about 0.062 Mt/yr. The large increase in bedload during those two wet years was most notable at the SRV gage (Table 3.4).

The SRV and SJJ gages are approximately 17 km from the confluence of the Sacramento and San Joaquin Rivers (the western most extent of the Delta) and 25 km upstream from the Mallard Island gage. In the 25 km between SRV/SJJ and Mallard Island, bedload transport rates may be reduced by sand mining operations and shipping canal dredging but increased by additional deposition of suspended-sediment.

There is permitted sand mining at the downstream edge of the Delta and Suisun Bay which affect the quantity of bedload reaching San Francisco Bay. Between 1999-2010, approximately 55,900 m^3/yr (0.084 Mt/yr) of bed-material sediment was mined between the San Joaquin River near the western edge of the Delta and Mallard Island (Bay Conservation and Development Commission data; Brenda Goeden, writ. comm.2015). The volume of sand mining for that reach has been steadily declining (from 103,000 m^3/yr (0.156 Mt/yr) in 1999 to 19,600 m^3/yr (0.0295 Mt/yr) in 2010) but on average during that period, the quantity of sand mining was about 47,900 m^3/yr (0.072 Mt/yr), nearly the amount estimated to exit the Delta at the SRV and SJJ (Table 3.4). Additional mining also takes place downstream of Mallard Island which would likely affect bedload transport into San Pablo Bay and other southern parts of San Francisco Bay.

Table 3.4. Bedload estimates from downstream-most gages in the Delta at Sacramento River at Rio Vista (SRV) and San Joaquin at Jersey Point (SJJ) and mass of bed-material removed from mining and dredging operations between these gages and Mallard Island (MAL). A dash (-) indicates that records were not available.

Year	Seaward bedload transport estimates (Mt/yr)			Bed-material removed by sand mining and dredging operations (Mt/yr)			Total seaward bedload – total removal[4]
	SRV	SJJ	Total (SRV+ SJJ)[1]	Sand mining (upstream of MAL gage)	San Joaquin River dredging[2]	Sacramento River dredging[3]	
1997	0.0348	0.0377	0.0725	0.0000	-	-	-
1998	0.128	0.0448	0.173	0.0000	-	-	-
1999	0.0181	0.0310	0.0491	0.156	-	-	-
2000	0.0286	0.0285	0.0571	0.132	0.0000	0.0371	-0.112
2001	0.0217	0.0255	0.0472	0.149	0.0000	0.203	-0.3052
2002	0.0231	0.0258	0.0488	0.133	0.0063	0.0420	-0.133
2003	0.0283	0.0283	0.0567	0.131	0.0000	0.0348	-0.110
2004	0.0375	0.0295	0.0671	0.0482	0.0000	0.0000	0.0188
2005	0.0408	0.0336	0.0744	0.0399	0.0000	0.0622	-0.0277
2006	0.133	0.0410	0.174	0.0571	0.0000	0.184	-0.0674
2007	0.0154	0.0301	0.0455	0.0562	0.0338	0.0006	-0.0451
2008	0.0160	0.0425	0.0585	0.0271	0.126	0.127	-0.222
2009	0.0175	0.0600	0.0775	0.0505	0.0463	0.0000	-0.0193
2010	0.0200	0.0637	0.0838	0.0295	0.0713	0.0000	-0.0170
Mean	0.0402	0.0372	0.0775	0.0722	0.0258	0.0628	-0.0833

1. Both the SRV and SJJ gages are approximately 17 km from the confluence of the Sacramento and San Joaquin Rivers (the western most extent of the Delta) and 25 km upstream from the Mallard Island gage. Between SRV/SJJ and Mallard Island, bedload transport rates may be affected by sand mining, dredging, and additional deposition.
2. Includes Scour and McCormack sites only
3. Includes Augusto and Decker sites only
4. column 4 minus columns 5-7

In addition to sand mining, the U. S. Army Corps of Engineers (USACE) periodically dredges the two deep water shipping channels along the Sacramento and San Joaquin Rivers. Annual volumes of material dredged from the shipping channels were obtained from USACE (2012) and, USACE-Sacramento District (Gary Kamai, writ. comm., 2013). The volumes of bed-material dredged in areas downstream of the gages are provided in Table 3.4. The total volume removed by dredging and sand mining between the SRV and SJJ gages and Mallard Island is roughly double the volume of bedload estimated to exit the Delta at the two gages.

The final factor affecting bedload exiting the Delta is the potential for additional deposition of suspended sediment downstream of the two gages (SRV and SJJ). Within the Delta, streamflow transitions from uni-directional riverine discharge to bi-directional tidal discharge (except in extreme high discharge events associated with winter storms). During this transition, suspended sediment drops out of suspension starting with the coarsest particles. Some of that sediment is deposited in the Delta, while some will continue downstream as bedload. We could not estimate how much of the suspended sediment in the area between the SRV/SJJ and the Mallard Island gages transitions to bedload before entering the San Francisco Bay.

In the 25 km between the stations where we calculate bedload and Mallard Island, the quantity of sediment removed by sand mining and dredging is larger than the estimated riverine supply (Table 3.4). We estimated bedload at Mallard Island for two sets of assumptions to provide upper and lower bounds. The upper estimate was made assuming sand mining and dredging do not affect bedload transport and that the bedload measured upstream passes through the 25 km reach downstream to Mallard Island (Column 4 of Table 3.4, mean = 0.078 Mt/yr).

The lower Mallard Island bedload estimate assumes that bedload replenishes all of the sediment removed by sand mining and dredging and that bedload can move upstream (landward) at Mallard Island (Column 5 of Table 3.4, mean = -0.083 Mt/yr, where the negative value indicates upstream bedload transport). For reaches such as this where removal exceeds upstream supply and discharge is bidirectional, upstream bedload transport is possible and any deficit caused by dredging may be filled by upstream transport from the Bay. This differs from the fluvial reaches of flood control channels on small tributaries around the Bay. In this case, discharge is unidirectional and any deficit caused by dredging was assumed to be made up by deposition of suspended sediment, thus effectively making transport of bedload to the Bay by some flood channels zero during some years or even zero over a long term period. Measurements of bedload at Mallard Island are needed to reduce this uncertainty indicated by the difference in the upper and lower bounds, and as discussed later, there are also many uncertainties about bedload transport in small tributaries.

Our best estimate of mean annual long-term sediment supply to San Francisco Bay at Mallard Island under current "climate normal" conditions is 0.58 Mt/yr. This is the product of the mean annual Delta outflow WY 1981-2010 (22,800 Mm^3/yr) and the current slope of the double mass plot (25.2 mg/L, Table 3.2). The range of seaward bedload at Mallard Island is -13% to 20% of the seaward suspended load (Table 3.1 and Table 3.4), so we assume the annual long-term bedload at Mallard Island ranges from -0.07 to 0.12 Mt/yr.

Sediment Supply from Bay Area Watersheds

Suspended and Bed Sediment Loads in Better-Sampled Small Tributaries

Suspended-sediment load and bed load were estimated for tributaries that ranged in size from 0.023 km^2 (an unnamed small tributary in Solano County) to 1,689 km^2 (Alameda Creek). As described in the methods, loads for the majority of small tributaries were estimated using sub-regional regression relations. Suspended-sediment loads estimates for a few of the larger better-sampled watersheds (Sonoma Creek, Napa River, Walnut Creek, Coyote Creek, Guadalupe River, San Francisquito Creek) are presented in more detail (Table 3.5) to give the reader an idea of the magnitude and variability of loads in individual watersheds and the overall structure of the database.

Loads vary considerably between years, the most extreme example here being San Francisquito Creek, a well-recognized phenomenon in small tributaries (McKee et al., 2003). Although size of watershed is a key factor in determining overall annual average loads, yield (load divided by the area of a watershed downstream from any reservoirs) varies considerably between watersheds. Yields vary from just 24 t/km^2 in Coyote Creek to 558 t/km^2 in Sonoma Creek, a phenomenon also well documented previously for the Bay Area (McKee et al., 2003; McKee et al., 2013). Also note that the yields for these small tributaries, and for the total area that drains the nine-county Bay Area, exceed the yield of suspended sediment delivered from the Central Valley via Mallard Island (9.1 t/km^2 of area downstream from reservoirs) by many-fold.

As shown in Table 3.5, Napa River alone is estimated to, on average, contribute 13% of the annual suspended-sediment loads to the Bay from the small tributaries, but that contribution can vary from 2.4% in WY 2014 to as large as 24% in WY 1995 when it is estimated that Napa River delivered close to 1 Mt. Inter-annual climatic variation plays a major role in this variable contribution not only in terms of generally wetter and drier years in the Bay Area as a whole but also that the North Bay can have a wetter year when the South Bay is having a drier year and vice versa. Indeed, just as the Central Valley climate and hydrology can be decoupled from the Bay Area, so can the climate within the Bay Area be different in the north, east, and south where the largest watersheds are found. For example, during WY 2017, based on USGS preliminary data, Guadalupe River (in the south) had a peak discharge of only about a 1:5-year storm (a little over 50% of the peak discharge of record). In contrast, Alameda Creek (in the east) sustained the second largest peak discharge on record (less than the WY 1998 peak discharge of 17,900 cfs by only 200 cfs), but in the Napa River in the north, the peak discharge was unremarkable for that system and 20,000 cfs less than the WY 1986 peak (the largest on record for that system).

Table 3.5 also shows that on average, Sonoma Creek, Napa River, Walnut Creek, and Alameda Creek deliver 40% of the annual loads from small tributaries despite being only 37% of the land area, but this percentage can vary from 29-50% depending on the climate year. Of these four watersheds, only Alameda Creek has an ongoing data collection program for both suspended and bed loads. The other three watersheds have suspended-sediment rating curves based on data collected in the 1950s, 1960s or 1970s. There have been a lot of land use and environmental policy changes in the intervening years that could have changed the way sediment is eroded and transported in these watersheds. The total suspended-sediment load delivered by all small tributaries WY1995-2016 is estimated to be 1.30+/-0.45 Mt/yr on average. This is less than the most recent regional estimate (WY1995-2010, 1.39+/-0.71 Mt/yr: McKee et al., 2013) partly due to changes to the computation methods but mostly due to less precipitation during the averaging period. But, please note that due to overlapping errors, these suspended-sediment loads estimates are functionally the same.

Two reference points for the estimates of sediment loads are the sediment TMDLs for the Sonoma Creek and Napa River that were prepared by the Water Board (SFBRWQCB, 2008; SFBRWQCB, 2009). The Sonoma Creek TMDL estimated a total sediment yield of 248 t/km^2 for 2005 (106,503 t/yr from a total watershed area of 430 km^2). That yield is about half the average from this report for the WY1995-2016 period (558 t/km^2). For the Napa River, the yield from the TMDL (461 t/km^2 for WY1994-2004) is much closer to the estimate from this report (429 t/km^2). The range in the yields for the Sonoma Creek is likely due to differences in the averaging period and methods (with associated error) as well as the high uncertainty inherent in sediment load estimates. Both estimates are considered valid. The difference between them highlights the uncertainty and inter-annual variability associated with sediment yield estimates.

Bedloads estimated for these watersheds show similar patterns as the suspended load (Table 3.6). Like suspended loads, bedloads also vary considerably between years. The paucity of data available to estimate bedload is striking; the only well-sampled watershed where these estimates might be considered reliable is Alameda Creek. However, even for this system, field measurements are lacking for discharges >3,000 cfs. In a similar manner to suspended-sediment, estimated bedload yields vary considerably between watersheds from 2.7-60 t/km^2. Walnut Creek is estimated to produce 20% of the annual average bed sediment load to the Bay from the small tributaries (111,000+/-68,000 t/yr) but that contribution can vary from 0% in drought years to as large as 39% in WY 2006. On average, Sonoma Creek, Napa River, Walnut Creek, and Alameda Creek are estimated to deliver 45% of the annual bed sediment loads from small tributaries despite being only 37% of the land area but this is estimated to vary from 10-58% depending on the water year (Table 3.6). Of these four watersheds, only Alameda Creek has an ongoing data collection program for bedloads. For the other three watersheds, bedloads were estimated using either a sub-regional rating curve (Sonoma Creek) or very limited historic data (Napa River and Walnut Creek). Given the importance of coarse sediment for beach nourishment projects, sand mining, and wetland restoration, these data gaps may need to be rectified.

Sediment Storage and Removal from Flood Control Channels

As described in the methods, considerable effort was expended through the FC 2.0 project to collate existing data on sediment storage and removal from key Bay Area flood control channels. Data from some of our larger watersheds are presented here to demonstrate the variable nature of this storage and removal as well as the available data (Table 3.7). Overall, we currently estimate an annual average (net) storage of about 29,000 t/yr and an annual removal rate of about 82,000 t/yr for a total of 111,000 t/yr (the similarity of this estimate to the regional bedload estimate is coincidental). Data on storage and removal, however, are lacking for many tributaries and are not being systematically (annually) collated for the region in any kind of regional database. In cases like Sonoma Creek, Napa River, and San Francisquito Creek, the estimates of zero storage, while our best judgement at this time, indicate the need for better estimates. It should also be noted that data are not available past WY 2013. The full data set for creeks, where it is available, can be downloaded from the FC website (floodcontrol.sfei.org).

Table 3.5. Estimated suspended-sediment loads in units of million metric tonnes (Mt/yr) in key larger, better-sampled tributaries in the Bay Area as compared to the total regional estimate. Yields (in t/km²) are load divided by the area upstream from the head of tide and downstream from reservoirs.

Water Year	Sonoma Creek		Napa River		Walnut Creek		Alameda Creek		Coyote Creek		Guadalupe River		San Francisquito Creek		All other tributaries		Bay Area total
	Sonoma		Napa		Contra Costa		Alameda		Santa Clara		Santa Clara		Santa Clara				
	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass
1995	0.45	12.7	0.84	23.8	0.13	3.8	0.34	9.7	0.041	1.2	0.053	1.48	0.043	1.205	1.6	46.2	3.5
1996	0.077	6.7	0.14	11.8	0.15	13.0	0.14	12.0	0.013	1.1	0.015	1.34	0.031	2.73	0.59	51.5	1.2
1997	0.17	6.8	0.36	14.2	0.32	12.8	0.19	7.5	0.029	1.1	0.036	1.45	0.040	1.58	1.4	54.6	2.5
1998	0.19	3.5	0.66	12.2	0.31	5.8	0.43	7.9	0.039	0.7	0.050	0.92	0.10	1.90	3.6	67.1	5.4
1999	0.049	6.5	0.11	13.9	0.015	2.0	0.049	6.5	0.0017	0.2	0.0018	0.24	0.027	3.53	0.51	67.1	0.76
2000	0.033	4.2	0.074	9.4	0.16	20.3	0.041	5.2	0.0078	1.0	0.0093	1.18	0.022	2.81	0.44	55.9	0.79
2001	0.014	8.8	0.015	9.3	0.014	8.8	0.0056	3.6	0.0020	1.3	0.0022	1.43	0.0053	3.37	0.10	63.5	0.16
2002	0.070	20.1	0.085	24.4	0.0052	1.5	0.0087	2.5	0.0011	0.3	0.0013	0.36	0.0070	2.01	0.17	48.7	0.35
2003	0.31	17.0	0.17	9.4	0.011	0.6	0.39	21.6	0.0096	0.5	0.012	0.66	0.012	0.64	0.91	49.7	1.8
2004	0.14	14.3	0.13	13.3	0.094	9.3	0.091	9.1	0.0066	0.7	0.0094	0.94	0.0082	0.82	0.52	51.6	1.0
2005	0.049	7.4	0.080	12.2	0.088	13.3	0.044	6.6	0.010	1.5	0.0062	0.95	0.024	3.70	0.36	54.2	0.66
2006	0.72	14.6	0.38	7.7	0.68	13.7	0.16	3.2	0.015	0.3	0.014	0.28	0.056	1.15	2.9	59.2	4.9
2007	0.0061	4.5	0.0053	3.9	0.018	13.0	0.011	8.1	0.0018	1.3	0.0017	1.26	0.0023	1.65	0.090	66.3	0.14
2008	0.099	15.7	0.037	5.9	0.036	5.8	0.042	6.7	0.0047	0.7	0.0056	0.89	0.0076	1.21	0.40	63.1	0.63
2009	0.020	9.2	0.025	11.9	0.018	8.7	0.012	5.5	0.0029	1.3	0.0029	1.36	0.0065	3.05	0.12	58.9	0.21
2010	0.084	13.2	0.052	8.1	0.037	5.8	0.071	11.1	0.0053	0.8	0.0089	1.40	0.011	1.75	0.37	57.8	0.64
2011	0.043	4.0	0.20	18.2	0.081	7.5	0.13	12.4	0.011	1.0	0.013	1.23	0.024	2.24	0.58	53.5	1.1
2012	0.017	5.8	0.025	8.5	0.043	14.9	0.013	4.5	0.0012	0.4	0.0026	0.88	0.0054	1.86	0.18	63.1	0.29
2013	0.19	15.3	0.10	8.2	0.23	19.0	0.067	5.5	0.0029	0.2	0.0049	0.40	0.011	0.93	0.61	50.4	1.2
2014	0.018	15.1	0.0028	2.4	0.011	9.4	0.0077	6.6	0.0016	1.3	0.0019	1.59	0.00031	0.26	0.074	63.3	0.12
2015	0.14	24.2	0.029	5.0	0.024	4.2	0.034	5.9	0.0036	0.6	0.0045	0.78	0.0063	1.08	0.34	58.2	0.58
2016	0.039	7.2	0.082	15.4	0.050	9.3	0.043	8.0	0.0026	0.5	0.0030	0.56	0.016	3.07	0.30	56.0	0.54
Minimum	0.0061	3.5	0.0028	2.4	0.0052	0.58	0.0056	2.5	0.0011	0.23	0.0013	0.24	0.00031	0.261	0.074	46	0.12
Maximum	0.72	24	0.84	24	0.68	20	0.43	22	0.041	1.5	0.053	1.6	0.10	3.7	3.6	67	5.4
Variation	118		297		130		77		36		41		336		49		46
Mean	0.13	10	0.16	13	0.11	8.9	0.11	8.1	0.0097	0.75	0.012	0.91	0.021	1.6	0.74	57	1.3
Total area (km²)	239		707		362		1,689		907		419		115		3607		8,045
Area downstream from reservoirs (km²)	239		381		359		958		403		255		79		3049		5,723
Yield (t/km²)	558		429		320		110		24		46		269		242		227

Note – 2 significant figures have been retained in these tables which is a good approximation of the relative accuracy of the data. But upon request, the data are available in MS EXCEL if more significant figures are of interest for a given tributary.

Table 3.6. Estimated bedload in units of metric tonnes (thousand t/yr) in key larger tributaries in the Bay Area as compared to the total regional estimate. Yields (in t/km^2) are load divided by the area upstream from the head of tide and downstream from reservoirs. To convert the loads shown in this table to units of million metric tonnes (Mt/yr), divide by 1,000.

Water Year	Sonoma Creek		Napa River		Walnut Creek		Alameda Creek		Coyote Creek		Guadalupe River		San Francisquito Creek		All other tributaries		Bay Area total
	Sonoma		Napa		Contra Costa		Alameda		Santa Clara		Santa Clara		Santa Clara				
	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass	%	Mass
1995	36	15	13	5.6	17	7.2	52	22	5	2.0	4.3	1.8	6.3	2.7	0.10	0.044	237
1996	6.1	6.2	5.3	5.4	20	20	17	17	1.4	1.4	2.0	2.0	4.7	4.7	0.043	0.043	99
1997	14	6.5	7.2	3.4	59	28	24	12	3.2	1.5	3.1	1.4	5.9	2.8	0.095	0.045	212
1998	15	3.7	11	2.6	49	12	71	17	4.4	1.1	4.2	1.0	15	3.7	0.24	0.059	410
1999	3.9	5.6	4.3	6.1	0	0	4.4	6.3	0.20	0.28	0.58	0.84	4.0	5.7	0.052	0.075	70
2000	2.6	3.7	3.1	4.4	25	35	5.4	7.7	0.88	1.2	1.5	2.1	3.2	4.6	0.029	0.041	71
2001	1.1	4.2	1.3	4.9	0	0	0.23	0.87	0.23	0.87	0.57	2.2	0.78	3.0	0.022	0.084	26
2002	5.6	19	3.8	13	0	0	1.2	4.3	0.13	0.44	0.31	1.1	1.0	3.5	0.017	0.058	29
2003	25	20	5.8	4.8	0	0	4.2	3.4	1.1	0.88	1.2	1.0	1.7	1.4	0.083	0.068	122
2004	12	13	4.8	5.5	13	15	7.4	8.5	0.74	0.84	1.0	1.1	1.2	1.4	0.047	0.054	88
2005	3.9	5.7	4.7	7.0	8.3	12	15	22	1.1	1.7	1.8	2.7	3.6	5.3	0.029	0.043	68
2006	58	12	11	2.3	185	39	15	3.3	1.7	0.36	3.1	0.65	8.4	1.8	0.19	0.041	475
2007	0.48	2.6	0.73	4.0	2.4	13	2.7	15	0.20	1.1	0.60	3.3	0.33	1.8	0.011	0.059	18
2008	7.9	13	2.2	3.5	5.6	9.1	4.3	6.9	0.53	0.86	0.91	1.5	1.1	1.8	0.039	0.064	62
2009	1.6	7.4	1.6	7.8	2.5	12	3.1	15	0.32	1.5	0.80	3.8	0.93	4.4	0.010	0.049	21
2010	6.7	11	3.3	5.7	5.7	10	7.5	13	0.60	1.0	1.4	2.3	1.6	2.7	0.032	0.054	59
2011	3.5	3.6	6.3	6.5	15	15	21	22	1.2	1.3	2.3	2.3	3.6	3.7	0.044	0.046	97
2012	1.3	4.1	1.7	5.2	6.9	21	1.9	5.6	0.13	0.40	0.63	1.9	0.78	2.4	0.020	0.059	33
2013	15	11	3.3	2.5	51	39	6.8	5.2	0.33	0.25	0.84	0.64	1.6	1.2	0.052	0.040	131
2014	1.4	11	0.57	4.3	1.3	10	0.38	2.8	0.18	1.3	0.32	2.4	0.044	0.33	0.0090	0.068	13
2015	11	21	1.8	3.2	3.4	6.3	4.6	8.4	0.41	0.75	0.52	1.0	0.90	1.7	0.032	0.058	54
2016	3.1	6.2	3.1	6.2	8.2	16	8.6	17	0.30	0.59	0.66	1.3	2.4	4.8	0.024	0.047	50
Minimum	0.48	2.6	0.57	2.3	0.00	0.00	0.23	0.87	0.13	0.25	0.3	0.64	0.044	0.33	0.0090	0.040	13
Maximum	58	21	13	13	185	39	71	22	4.6	2.0	4.3	3.8	15	5.7	0.24	0.084	475
Variation	119		24		-		310		36		14		346		27		36
Mean	11	9.6	4.6	4.1	22	20	13	11	1.1	1.0	1.5	1.3	3.1	2.8	0.056	0.050	111
Total area (km^2)	239		707		362		1,689		907		419		115		3,607		8,045
Area downstream from reservoirs (km^2)	239		381		359		958		403		255		79		3,049		5,723
Yield (t/km^2)	0.045		0.012		0.060		0.013		0.0027		0.0058		0.040		0.000018		0.019

Note – 2 significant figures have been retained in these tables which is a good approximation of the relative accuracy of the data. But upon request, the data are available in MS EXCEL if more significant figures are of interest for a given tributary

Table 3.7. Sediment storage and removal in the fluvial portions of larger small tributaries in metric tonnes (t) as compared to the sum of all available information for the region. To convert the loads shown in this table to units of million metric tonnes (Mt), divide by 1,000,000.

Water Year	Sonoma Creek		Napa River		Walnut Creek		Alameda Creek		Coyote Creek		Guadalupe River		San Francisquito Creek		All other tributaries		Bay Area total	
	Sonoma		Sonoma		Contra Costa		Alameda		Santa Clara		Santa Clara		Santa Clara					
	Storage	Removal	Storage	Removal	Storage	Removal	Storage	Removal	Storage	Removal	Storage	Removal	Storage	Removal	Storage	Removal	Storage	Removal
1995	0	0	0	0	7,540	48,300	44,900	0	4,530	0	3,320	0	1,190	0	8,960	17,900	70,500	66,100
1996	0	0	0	0	8,530	0	17,700	0	1,440	0	1,200	0	430	0	4,820	29,900	34,100	29,900
1997	0	0	0	203,000	19,000	0	24,000	0	1,760	0	1,430	0	514	0	11,300	76,900	58,000	280,000
1998	0	0	0	0	18,200	0	55,800	95,400	2,700	0	2,100	0	752	0	25,000	74,800	105,000	170,000
1999	0	0	0	178,000	767	0	6,780	85,400	593	0	254	0	91	0	2,250	0	10,700	263,000
2000	0	0	0	0	9,270	0	7,660	134,000	1,720	0	791	0	284	0	2,350	18,700	22,100	153,000
2001	0	0	0	0	693	0	927	50,900	470	0	386	0	139	0	344	70,400	2,960	121,000
2002	0	0	0	0	261	0	1,650	0	155	0	585	0	210	0	587	12,900	3,450	12,900
2003	0	0	0	0	530	0	63,500	0	647	0	1,910	0	686	0	10,200	26,000	77,500	26,000
2004	0	0	0	0	5,380	0	15,500	0	1,100	0	1,460	0	523	0	2,560	40,800	26,600	40,800
2005	0	0	0	0	4,810	0	9,050	0	1,700	0	871	6,27	313	0	944	2,500	17,700	8,770
2006	0	0	0	0	43,200	48,300	27,400	0	2,530	0	2,080	13,560	748	0	6,640	19,200	82,500	81,000
2007	0	0	0	0	1,010	60,800	2,350	0	300	0	218	0	78	0	687	41,000	4,600	102,000
2008	0	0	0	9,920	2,100	0	8,170	0	623	0	832	559	299	0	1,520	19,100	13,500	29,500
2009	0	0	0	0	1,050	0	2,480	0	479	0	404	1,960	145	0	692	7,150	5,250	9,110
2010	0	0	0	0	2,160	0	13,100	0	893	953	1,350	2,970	484	0	2,760	29,900	20,700	33,800
2011	0	0	0	48,100	4,830	0	26,000	0	1,860	0	2,070	2,710	743	0	5,590	20,600	41,100	71,400
2012	0	0	0	0	2,530	0	2,470	0	195	0	340	6,030	122	0	1,810	16,500	7,470	22,600
2013	0	0	0	38,000	14,200	0	12,100	0	490	0	717	0	257	0	5,050	424	32,800	38,400
2014	0		0		623		0		0		0		0		1,380		2,000	
2015	0	No data	0	No data	1,380	No data	0	No data	0	No data	0	No data	0	No data	9,670	No data	11,100	No data
2016	0		0		2,910		0		0		0		0		10,000		13,000	
Total	0	0	0	477,000	151,000	157,000	342,000	366,000	24,200	953	22,300	34,100	8,010	0	115,000		662,000	1,560,000
Mean	0	0	0	25,100	6,860	8,280	15,500	19,300	1,100	50	1,010	1,790	364	0	5,240		30,100	82,100

Note – 3 significant figures have been retained in these tables to aid in any post processing of the data by others. Given challenges with data availability and errors associated with bed load computation methods, data are probably not accurate beyond 2 significant figures.

Net Annual Loads

Suspended-sediment loads entering the Bay at the head of tides from the small tributaries are collectively estimated to have varied by 46-fold and averaged 1.30+/-0.45 Mt/yr over the period WYs 1995-2016 (Table 3.8). This large variation in sediment load is mostly driven by year-to-year climatic variability. These region-wide estimates are 9% less than those published previously for the period WYs 1995- 2010 (1.39+/-0.71 Mt: McKee et al., 2013). Estimated average annual freshwater river discharge for the small tributaries for WYs 1995-2016 was 1.51 km^3/yr, 18% less than that reported by McKee et al. (2013) for WYs 1995-2010 (average = 1.84 km^3/yr). Most of this change can be attributed to the 2012-2016 drought, but as discussed in the methods section, there have been methodological improvements, as well as additional data used in the computations that were not available for previous efforts. Just four years over the 22-year record (WYs 1995, 1997, 1998, and 2006) were responsible for transport of 57% of the suspended-sediment load at the same time as 39% of the freshwater discharge was delivered. It took only eight years and 60% of the discharge to deliver more than 75% of the 22-year total sediment load. Based on the USGS data on grainsize in our Bay Area watersheds, most of this suspended sediment (~80%) was likely transported in grain sizes smaller than 62.5 microns (silts and clays).

Bedload (mostly sand and gravel grain sizes) is estimated to be 0.111+/-0.068 Mt/yr or 8% of the total annual suspended-sediment load. Based on data compiled from the flood control agencies (data are of variable quality and availability) during the FC 2.0 project (SFEI-ASC, 2016), our current best estimate for the fate of this sediment either as net channel storage or as net sediment removed is 0.030 and 0.082 Mt/yr. Thus, bedload supply is approximately equal to the average amount of sediment stored or removed from flood control changes. Therefore, assuming that net sediment storage and dredge sediment removal by the flood control agencies is dominated by sand and gravel grain sizes in the fluvial portions of most flood control channel systems (SFEI-ASC, 2016), very little to none of the bedload from the watersheds is being delivered to the Bay (on average). This is likely not true for individual channels and for individual water years, but when averaged over the region as a whole and over 22 year, there appears to be a net of zero bedload supply on average.

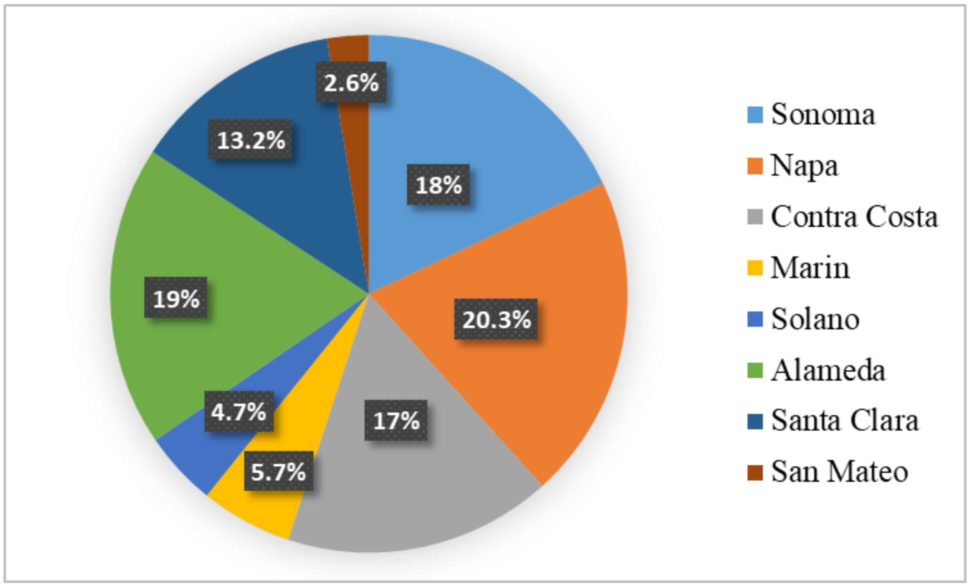
Although these annual average estimates are very informative, the annual sediment budgets are highly variable. The data suggest that during the dry years that follow wet years, the mass of sediment removed by the flood control agencies can rival the total amount delivered by all tributaries collectively (as illustrated by WYs 2001 and 2007 when 66% of the fluvial sediment supply for that year was removed). For this report, we are interested in decadal scale sediment budgets and benefits in the Bay, so it is more practical to consider net long-term average supply. Other applications, such as habitat restoration and shoreline management, would likely benefit from data on annual timeframes so monitoring programs should collect data at least annually.

Table 3.8. Summary of sediment loads (Million metric tonnes, Mt) entering the Bay at the head of tides from all small tributaries that drain to the Bay from the nine-county urbanized Bay Area.

Water Year	Discharge	Suspended-sediment load	Discharge-weighted mean annual SSC	Bedload		Total fluvial sediment load	Estimated net fluvial flood control channel storage		Fluvial flood control channel sediment removal		Net total sediment supply to the Bay
	(Million m³)	(Mt)	(mg/L)	(Mt)	Fraction of total	(Mt)	(Mt)	Fraction of total	(Mt)	Fraction of total	(Mt)
1995	3,658	3.5	968	0.24	6.3%	3.8	0.070	1.9%	0.066	1.8%	3.6
1996	2,153	1.2	536	0.099	7.9%	1.3	0.034	2.7%	0.030	2.4%	1.2
1997	2,443	2.5	1,026	0.21	7.8%	2.7	0.058	2.1%	0.28	10%	2.4
1998	3,677	5.4	1,476	0.41	7.0%	5.8	0.10	1.8%	0.17	2.9%	5.6
1999	1,333	0.76	570	0.070	8.4%	0.83	0.011	1.3%	0.26	32%	0.56
2000	1,242	0.79	633	0.071	8.2%	0.86	0.022	2.6%	0.15	18%	0.68
2001	536	0.16	293	0.026	14%	0.18	0.0030	1.6%	0.12	66%	0.059
2002	1,153	0.35	303	0.029	7.7%	0.38	0.0034	0.91%	0.013	3.4%	0.36
2003	1,672	1.8	1,095	0.12	6.2%	2.0	0.078	4.0%	0.026	1.3%	1.8
2004	1,339	1.0	750	0.088	8.0%	1.1	0.027	2.4%	0.041	3.7%	1.0
2005	1,812	0.66	362	0.068	9.4%	0.72	0.018	2.4%	0.0088	1.2%	0.70
2006	3,299	4.9	1,494	0.47	8.8%	5.4	0.083	1.5%	0.081	1.5%	5.2
2007	445	0.14	306	0.018	12%	0.15	0.0046	3.0%	0.10	66%	0.048
2008	845	0.63	747	0.062	8.9%	0.69	0.014	2.0%	0.030	4.3%	0.65
2009	637	0.21	332	0.021	9.0%	0.23	0.0053	2.3%	0.0091	3.9%	0.22
2010	1,220	0.64	522	0.059	8.4%	0.70	0.021	3.0%	0.034	4.9%	0.64
2011	2,086	1.1	523	0.10	8.2%	1.2	0.041	3.5%	0.071	6.0%	1.1
2012	632	0.29	461	0.033	10%	0.32	0.0075	2.3%	0.023	7.0%	0.29
2013	1,010	1.2	1,202	0.13	9.7%	1.3	0.033	2.4%	0.038	2.9%	1.3
2014	281	0.12	419	0.013	10%	0.13	0.0020	1.5%	Unknown		0.13
2015	672	0.58	864	0.054	8.6%	0.63	0.011	1.7%	Unknown		0.62
2016	1,086	0.54	494	0.050	8.6%	0.59	0.013	2.2%	Unknown		0.57
Total	33,230	29		2.4		31	0.66		1.6		29
Min	281	0.12	293	0.013	6.2%	0.13	0.0020	0.91%	0.0088	1.2%	0.048
Max	3,677	5.4	1,494	0.47	14%	5.8	0.10	4.0%	0.28	66%	5.6
Variation	13	46	5.1	36	-	45	-	-	-	-	116
Median	1,231	0.71	553	0.069	8.5%	0.8	0.019	2.2%	0.041	3.9%	0.67
Mean	1,510	1.30+/-0.45	859	0.111+/-0.068	7.9%	1.41	0.030	2.1%	0.082	5.8%	1.31

Proportional Supply to the Bay Using GIS

Regional-scale loads are of interest from a net Bay budget standpoint as managers and policy makers grapple with issues such as Bay dredging and disposal, and sand mining. Wetland restoration design engineers and managers, however, are perhaps more interested in loads at the scale of county margins or finer. As such, the database developed for this study was linked to a GIS to allow managers to aggregate estimates of sediment loads, storage, and removal for any area on the Bay margin of interest. Data will be made available in GIS format upon request. To provide an example of this, here we illustrate the total loads and yields estimates on a county basis (Figure 3.4). Comparing the yields for different counties illustrates spatial variability in sediment supply. Some of this variability is caused by geological and erosional variations and some is caused by year-to-year climatic variability. Future studies could normalize the loads by length of coastline for a first approximation of the relative magnitude of supply to restoration areas and operational landscape units along the Bay margin.



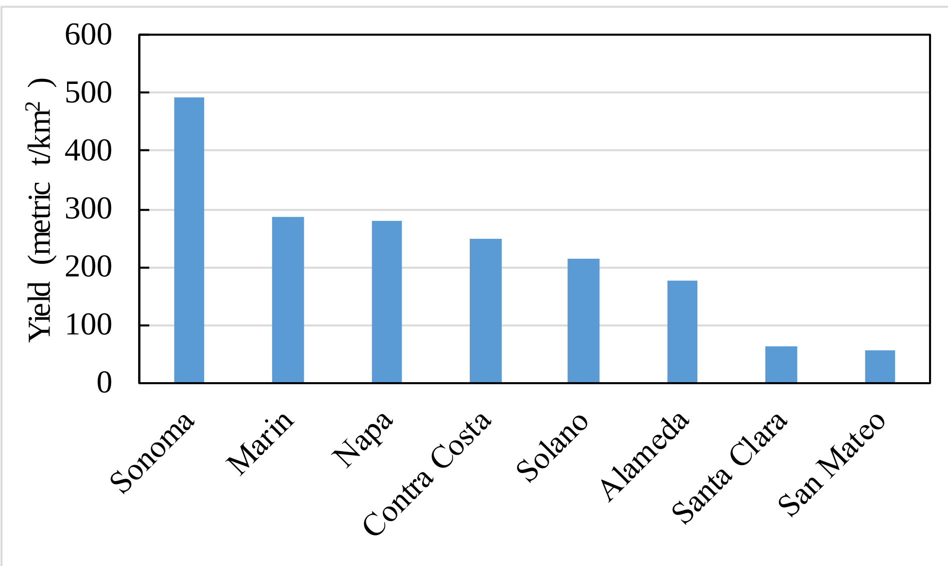


Figure 3.4. Proportional total sediment loads (top) and yields (bottom) by county in which discharge to the Bay is located.

Past Trends in Sediment Supply from Bay Area Watersheds

Regional Trends for All Small Tributaries Combined

Given the climatic variability of northern coastal California, it is difficult to determine trends in small tributary sediment loads just from a visual graphical analysis (Figure 3.5). Drought in much of the 2000s reduced discharge and suspended-sediment loads. Discharges and loads averaged ~2,000 Mm^3 and 1.9 Mt/yr respectively in the first 12 years (WY1995-2006); during the 10 years that followed (WY2007-2016), average discharge and loads were 0.891 Mm^3/yr and 0.54 Mt/yr. During the latter drought period (WY 2012-2016), estimated discharge of the small tributaries was about 48% of the estimated 1981-2010 normal (1,549 Mm^3/yr) (Wu et al., 2017). This impacted loads of suspended sediments, which for that period are estimated to be 0.55 Mt (less than half the annual average). Temporal trends aren't evident in the discharge-weighted SSC plot. Double mass plots of the regional sum cannot be developed because much of the load was computed using rating curves that relate mass to discharge. However, field-measured data and loads computed by the USGS for individual tributaries can be explored for trends using double mass plots as discussed below.

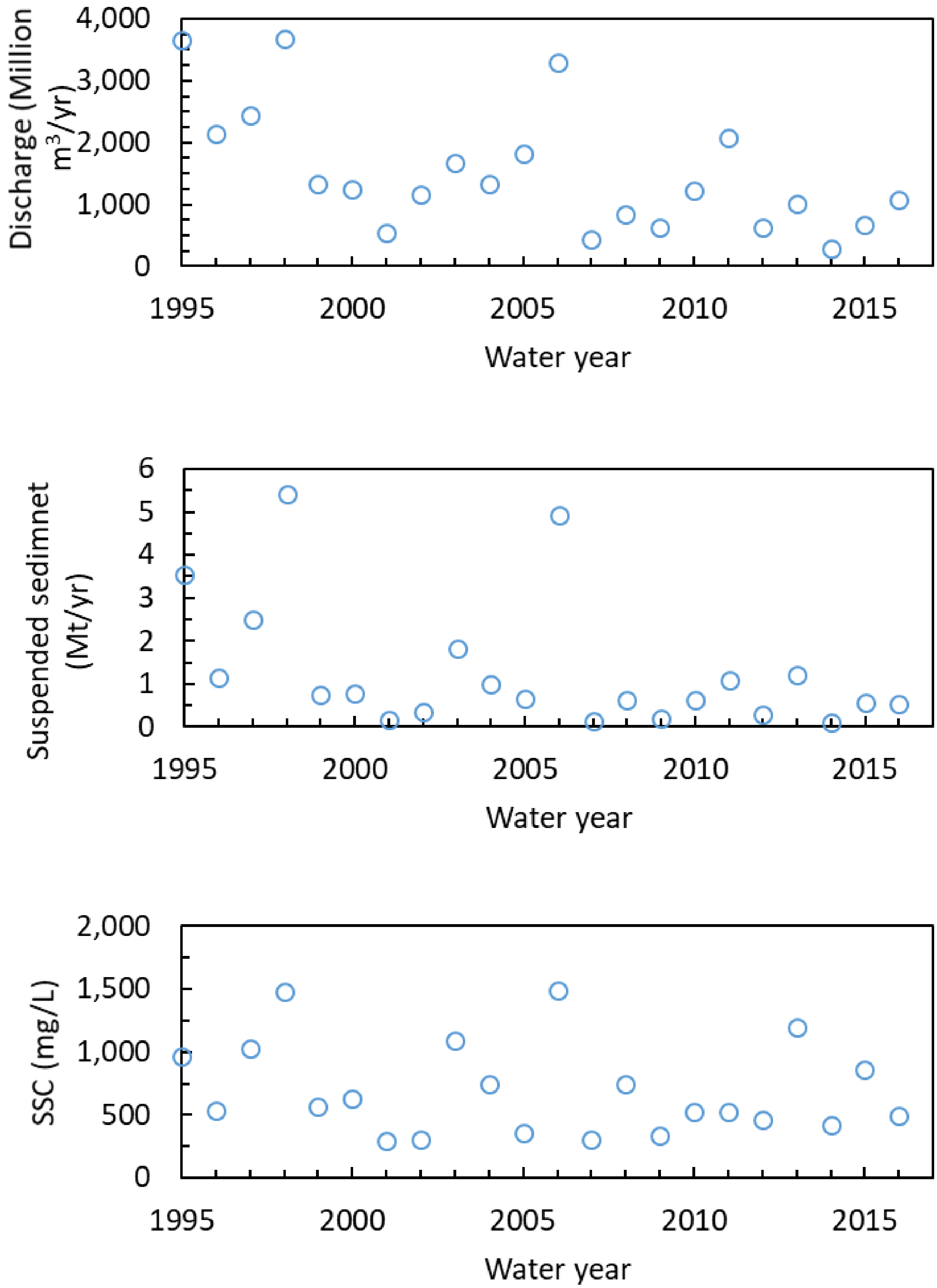


Figure 3.5. Annual discharge, suspended-sediment load, and discharge-weighted mean SSC estimated for the small tributaries discharging to San Francisco Bay from the nine adjacent counties.

Trends in Individual Small Tributary Watersheds

In a similar manner to the Central Valley loads at Mallard Island, double mass plots were made for six small tributaries to compare cumulative water discharge and cumulative sediment load to evaluate past changes and current trends (Walling and Fang 2003, McKee et al.2013). Unlike the single location and the continuous record for Mallard Island, the data available for local small tributaries are sparse and have time gaps (except Cull Creek). Most of the sediment at the Cull Creek and San Lorenzo Creek gages, however, is trapped behind reservoirs and is not presently available to the Bay. In addition, data are not available for any North Bay tributaries except Corte Madera Creek.

With these weaknesses in mind, double mass plots are presented to explore trends in tributaries with a suitable amount of data (Figure 3.6). The data available present evidence for non-stationarity at each location in relation to periods of increased and decreased erosion. However, each tributary in the Bay Area has a unique climatic setting and land use history and so no regional trends are evident.

- The plot for **Alameda Creek** shows that a very large storm occurred in WY 1958 releasing the largest load of any measured year. Although there may have been perturbations during the long period of missing data (WYs 1974-1999), the production of sediment appeared to remain stable through to WY 2003 with the exception of the drought period of WYs 2000-2002. The large floods of WY 2003 appear to have released sediment at a similar rate to WY 1958. The sediment production for this tributary for the period WY 2004-16 appears to have settled to the lowest average annual rate of all the available data.
- The data from **Cull Creek** do not appear to show any effects of the 1987-1994 drought period but do suggest a lowering of sediment production beginning WY 1999 (but still with a flood effect in WY 2003).
- The data from **San Lorenzo Creek** appear to reveal repeated patterns of increased and decreased sediment production. The periods WY 1981-83 and WY 1998-99 appear to be similar to the periods WY 1984-85, 1987-93, and 2000-02. The flood years of 1986 and 2003 showed increased sediment transport relative to discharge. Unlike the changes for Alameda Creek and Cull Creek, which may reflect changes in discharge associated with a gradual change in climate or land use and land management, the up and down changes in sediment production must be associated with changes in erosion.
- The double mass plots for **Guadalupe, Coyote,** and **Corte Madera** seem to indicate lower sediment production in recent years (since WY2007) relative to earlier periods.

The unique history for each small tributary adds challenges to a regional interpretation. They differ from the data set for Mallard Island, which represents the sediment loads that results from all the cumulative natural and anthropogenic influences for a single very large watershed measured at a single location.

Overall, if these watersheds are “representative”, it appears that erosion and sediment transport rates have decreased over time with the exceptions of drought periods and very high discharge years. But is the assumption of representativeness reasonable and have loads relaxed to a new equilibrium rate? One possible explanation is that decreasing loads reflect the diminishment of a 20th century sediment pulse from agriculturalization, deforestation, and urbanization in the watersheds (Schoellhamer 2011). Suspended-sediment load in Guadalupe River has decreased by a factor of 4–8-fold between observations made from 1957 to 1962 and more recent observations between 2003 and 2008 (Schoellhamer, 2011). Porterfield (1980) reported a mean yield for Guadalupe River for WYs 1957–1966 of 103 t/km^2, about 4-fold greater than the mean yield we computed for this report for WYs 1995–2016 despite the average discharge during the WY 1957-66 period (21.3 Mm^3) being 33% of the WY 1995- 2016 period (64.4 Mm^3).

We suggest that more thorough trend analysis that takes into account both climatic fluctuations and land use change is needed to explore this topic in more depth. Warrick (2015) discussed how large changes in water and sediment supplies can occur without any change in the coefficients of the rating curves. In addition, he pointed out that increases in discharge occur as a result of urbanization that may have little influence on sediment erosion and supply to the channels. The result is that loads can remain constant over time even if suspended-sediment concentrations trend downwards. Thus, he cautioned that trend analyses using sediment rating curves must include assessments of all three components (the time-dependent rates and trends of river water, sediment concentrations and sediment load). Furthermore, these trends when observed must be linked temporally to changes in land and water management or climate (real events that cause the change).

In summary, rating curves can be used for such a trend analysis if extreme care is taken (Warrick and Rubin, 2007; Warrick et al., 2013; Warrick, 2015) but such a level of effort, while likely to be fruitful, was well beyond the resources available for this report. So at this time, we have to conclude that we have evidence for a trend in loads relative to discharge but we cannot say what the cause is, if the cause is consistent across all tributaries, and if that trend represents a permanent change or if loads will again increase during a future climatically wet period (which often last 3-5 years; McKee et al., 2003).

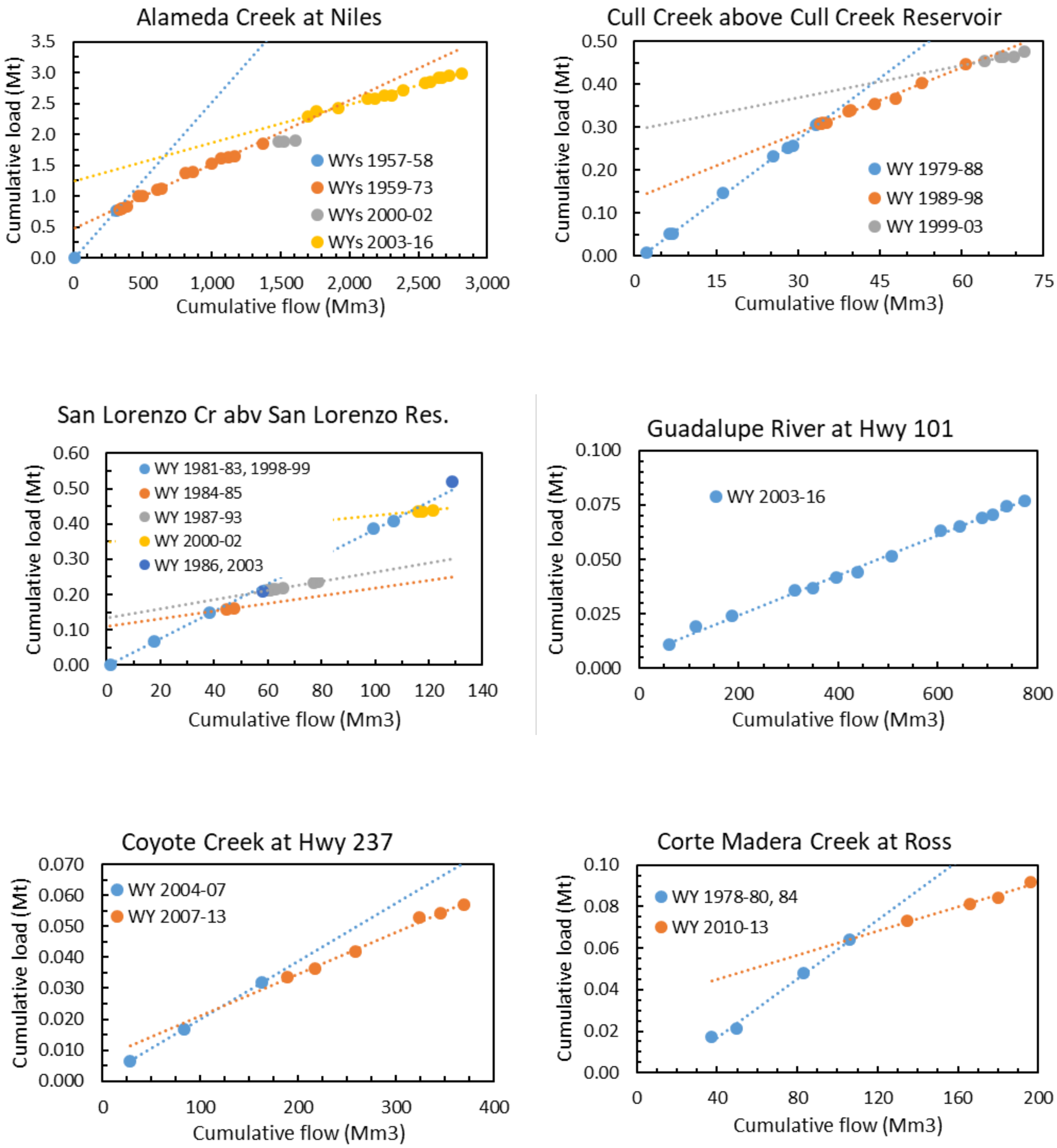


Figure 3.6. Double mass diagram for six individual small tributaries. Different lines on the same plot indicate periods with continuous data that are separated by data gaps.

Sediment Transport Between Subembayments

Dumbarton Bridge

During the recent drought in California from WY 2013 to WY 2016, landward sediment flux (i.e. sediment import) into Lower South Bay was greater than WY 2009 – 2011. A total of 0.71 Mt (95% confidence interval 0.41 – 1.0 Mt) of sediment import occurred from WY 2009-2011 and 1.2 (0.27 – 2.3) Mt of sediment import occurred from WY 2013-2016 (Livsey et al. in review). These results are in review, provisional, and subject to revision; detailed results are deferred for future publication. The results do concur with previous observations in Lower South Bay that found during wetter years with more freshwater discharge from the Central Valley sediment import decreased, while during drier years sediment import increased (Shellenbarger et al. 2013). These data do not include exceptionally large discharge from small tributaries, so a scenario where large storms and resulting discharge exports sediment has not been observed. The data are not of sufficient length to evaluate the decadal trend of sediment import.

Benicia Bridge

Suspended-sediment flux at the Benicia Bridge depends on freshwater flow to the estuary. During wet years such as WY2006 and WY2011 (Table 3.9), suspended sediment is exported from Suisun Bay (Figure 3.7). During dry years such as the WY2012-2016 drought, landward transport by gravitational circulation is greater than seaward transport by river discharges and Suisun Bay imports sediment at its seaward boundary.

Table 3.9. Seaward suspended-sediment loads at Mallard Island and Benicia Bridge and deposition in Suisun Bay, WY 2001-2016. Mallard Island is the landward boundary of Suisun Bay, Benicia Bridge is the seaward boundary, and they are the primary external sources and/or sinks of suspended sediment for Suisun Bay.

Water Year	Delta Outflow at Mallard Island (Mm^3)	Mallard Island suspended-sediment load (Mt)	Benicia Bridge suspended-sediment load (Mt)	Net Deposition (Mt)
2002	11,300	0.31	-2.09	2.40
2003	17,400	0.55	1.34	-0.79
2004	18,600	0.64	0.87	-0.23
2005	19,000	0.43	0.95	-0.52
2006	51,000	1.41	10.38	-8.97
2007	7,640	0.12	-2.87	2.99
2008	8,310	0.22	-2.73	2.95
2009	8,440	0.16	-2.50	2.66
2010	12,500	0.31	-1.95	2.26
2011	33,200	0.60	4.61	-4.01
2012	9,940	0.19	-2.32	2.51
2013	11,300	0.29	-2.10	2.39
2014	5,290	0.10	-3.02	3.12
2015	7,690	0.19	-1.96	2.15
2016	14,000	0.50	-0.94	1.44
Mean	**15,700**	**0.40**	**-0.29**	**0.69**

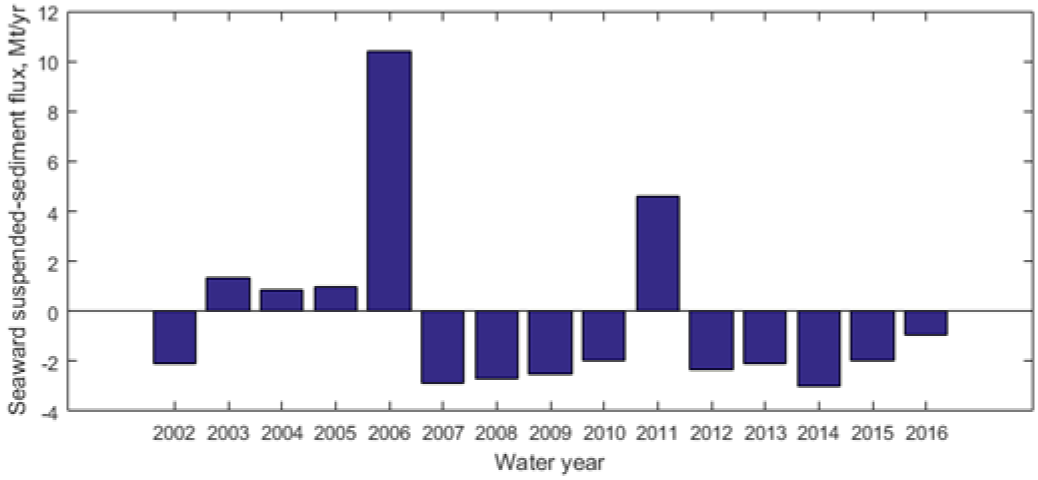


Figure 3.7. Estimated seaward suspended-sediment flux at the Benicia Bridge for water years 2002-2016.

The cumulative sediment deposition in Suisun Bay is the difference in suspended-sediment flux between Mallard Island and Benicia Bridge (Figure 3.8). High discharge years in 2006 and 2011 export sediment and create net erosion relative to the start of WY 2002 (October 1, 2001). During low discharge years Suisun Bay imports sediment from its landward and seaward boundaries and there is net deposition. From WY 2002 to WY 2016 Suisun Bay gained about 10 Mt of sediment. Assuming a bulk density of 850 kg/m^3 for the mostly muddy bottom sediment in Suisun Bay (Porterfield 1980), and deposition takes place uniformly over the mean tide surface area of Suisun Bay which is 169.6 Mm^2 (https://sfbay.wr.usgs.gov/sediment/sfbay/geostat. html), this would be an average depositional depth of 7 cm.

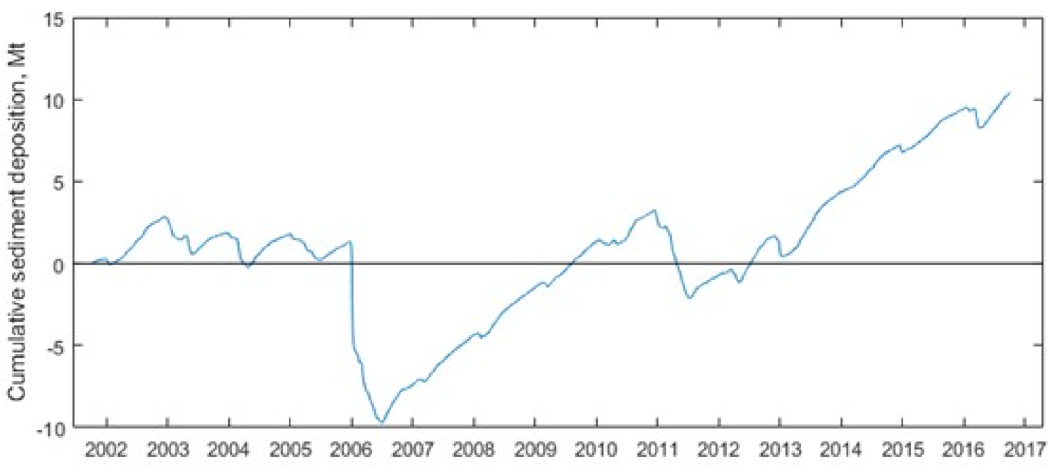


Figure 3.8. Cumulative sediment deposition in Suisun Bay since October 1, 2001. Negative values indicate erosion.

Suisun Bay deposition is inversely correlated with Delta outflow (Figure 3.9). Mean annual Delta outflow for WY 1981-2010 (22,800 Mm^3) was used with Figure 3.7 to estimate that the mean annual long-term deposition rate of Suisun Bay under current conditions is -1.26 Mt/yr which is erosional. Assuming a bulk density of 850 kg/m^3 (Porterfield 1980), the present net erosion rate is 0.87 cm/yr. For 1942-1990, Cappiella et al. (1999) found the erosion rate in Suisun Bay was 1.2 cm/yr. The decrease in net erosion rate between the periods 1942-1990 and 1981-2010 is likely due to the diminishment of the hydraulic mining sediment pulse.

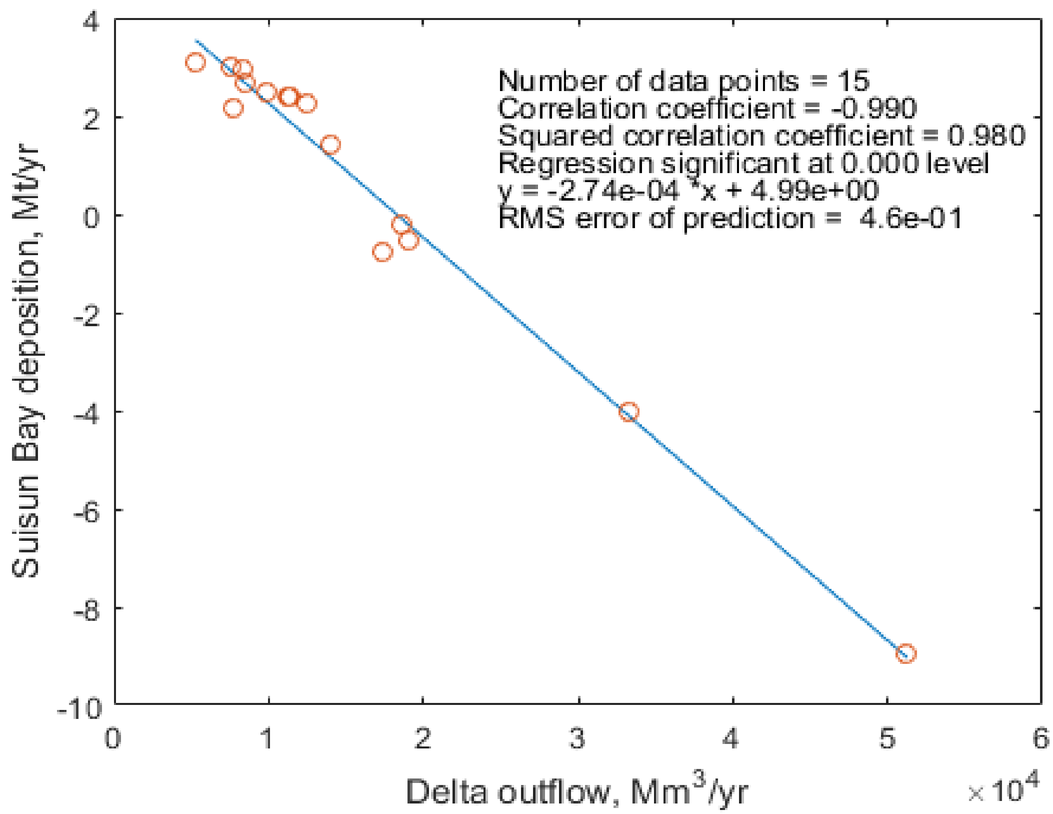


Figure 3.9. Suisun Bay deposition as a function of Delta outflow. Data are from Table 3.9.

4. Discussion

What are the magnitudes and sources of fine and coarse sediment transported to San Francisco Bay?

Net sediment supply to San Francisco Bay from terrestrial sources during the most recent 22-year period (WY 1995-2016) is summarized in Table 4.1. Taking into account our estimates of errors associated with measurements and estimation methods, the 22-year average load of suspended-sediment and bedload (total net load) during this period was between 1.1 and 2.8 Mt/yr with a best estimate of 1.9 Mt/yr. Net bedload supply, after accounting for removal and storage in flood control channels, was a small fraction of the total supply (functionally 0% after errors are taken into account). During this 22-year period, the majority of the sediment supply (63%) was from small tributaries (Figure 4.1). The individual tributaries that supplied the most sediment appear to be Sonoma Creek and Napa River which are estimated to account for 22% of the small tributary load and 14% of the total load. Net supply from the Delta was 37% of the total supply for this 22-year period. The delivery points are Mallard Island for sediment from the Delta and the head of tides for sediment from each of the hundreds of small tributaries.

In this synthesis, the Bay was defined as everywhere downstream from the head of tide in small tributaries. However, it is known that net suspended load will be affected by the tidal reach of the small tributary. Previous work in Corte Madera Creek has shown about 50% of fluvial suspended load can be trapped within the tidal reach (Downing-Kunz and Schoellhamer, 2015). Some of this load is then removed by flood control agencies. Thus, due to this removal, the load coming from small tributaries described in this synthesis report could be considered an upper bound if the sediment removed from tidal flood channels is not reused somewhere within the tidal limits of the Bay.

The finding that, on average, small tributaries have supplied more sediment to the Bay than the Delta is important but not new (McKee et al., 2013). During the Gold Rush and perhaps through to the 1980s, about 80% of the supply was estimated to be from the Central Valley (Porterfield, 1980). But land and water management have continued to evolve (Krone, 1996) and the sediment wave associated with the Gold Rush has diminished (Schoellhamer, 2011). In addition, the coastal mountains of California and around the Bay are steep, tectonically active and composed of relatively erodible marine sedimentary and metasedimentary rocks, in contrast to the Central Valley watershed that is dominated by highly indurated granitic, metasedimentary, and metavolcanic rocks in the western-facing slopes of the Sierra Nevada Mountains (McKee et al., 2013).

Water management is quite different between the Bay Area and Central Valley watersheds. About 48% of the Central Valley watershed is upstream from dams that are designed to capture, delay and diminish discharge from spring snowmelt and so eliminate or attenuate many of the peak discharges that are normally crucial for sediment transport. Central Valley dams likely skew the sediment transport relationship more towards large events than the historical natural condition. Medium sized events (which occur or are exceeded every ~2–10-years, called the return interval) that might previously have constituted a range of ‘dominant discharges’ for sediment transport are now absorbed by the many dams, but events like the 1997 floods exceed the flood storage capacity and trigger big releases, forming the new dominant discharges. While peak discharges from the Central Valley have been attenuated by dams, those from the coastal small tributary watersheds have been amplified by urbanization and hydromodification. Despite discharge attenuation by dams, the largest discharges from the Central Valley watershed still occur when warm rains fall on accumulated snow typically in the months of January through April, whereas runoff from coastal small tributaries is usually the result of sustained heavy coastal Pacific rainfall falling on saturated soils in December, January, and February.

The result of all the anthropogenic, geologic, and climatic differences is that, although small tributaries together comprise just 5% of the total watershed area and, for this 22-year period, 6.6% of the annual freshwater discharge, small tributaries now dominate the sediment supply. This notion is also consistent with the diminishment of the sediment pulse from hydraulic mining in the Sacramento Valley (Schoellhamer et al., 2013).

Another factor contributing to the extraordinary influence of small tributaries is the way that they deliver sediment. Discharge from small tributaries is very small in comparison to the volume of the Bay, and the load that small tributaries supply is delivered via wetland sloughs and channels to the mudflats on the margin of the Bay. The majority of this sediment delivered from small tributaries is more likely to be trapped in the Bay compared to supply from the Central Valley. In contrast, discharge from the Central Valley can cause a freshening of the North Bay and, if a portion is flushed directly through the Bay during larger discharges, cause a plume of suspended sediment extending out into the Gulf of the Farallones (Ruhl et al., 2001).

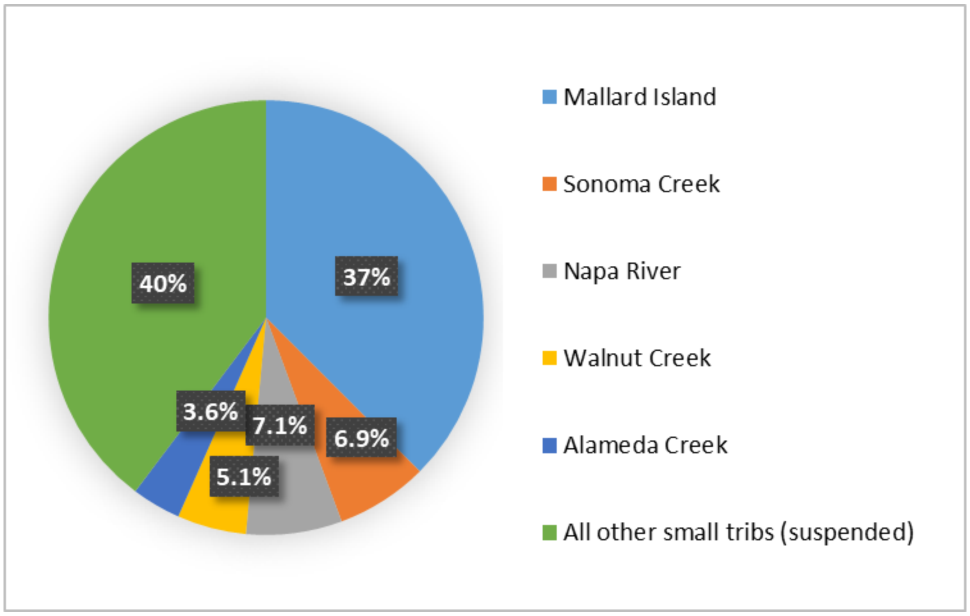


Figure 4.1. Net proportional total loads to the Bay from key large tributaries after accounting for storage and removal of sediment from flood control channels. Total load is the sum of suspended load and bedload. Data from Table 4.1.

Table 4.1. Summary of net mean annual total loads to San Francisco Bay by pathway taking into account storage and active removal by dredging. Confidence intervals for the estimates are shown in parentheses. Data are for WY 1995-2016 except where noted. Please see the methods section for details on error estimation methods.

	Suspended load (Mt/yr)	Bedload (Mt/yr)	Net total load to the Bay (Mt/yr)
Mallard Island	0.73 (0.5 to 0.96)	0 (-0.083 to 0.0771)[1]	0.73 (0.42 to 1.0)
Local tributaries[2]			
Sonoma Creek	0.13 (0.10 to 0.166)	0 (-0.0071 to 0.0071)	0.13 (0.093 to 0.17)
Napa River	0.14 (0.10 to 0.17)	0 (-0.0024 to 0.0024)	0.14 (0.10 to 0.18)
Walnut Creek	0.10 (0.075 to 0.125)	0 (-0.011 to 0.011)	0.10 (0.064 to 0.14)
Alameda Creek	0.071 (0.053 to 0.088)	0 (-0.0066 to 0.0066)	0.071 (0.046 to 0.10)
Coyote Creek	0.0086 (0.0064 to 0.0107)	0 (-0.00073 to 0.00073)	0.0086 (0.0057 to 0.011)
Guadalupe River	0.0090 (0.0067 to 0.0112)	0 (-0.00077 to 0.00077)	0.0090 (0.0060 to 0.012)
San Francisquito Creek	0.021 (0.016 to 0.026)	0 (-0.0021 to 0.0021)	0.021 (0.014 to 0.028)
All other small tributaries	0.73 (0.40 to 1.06)	0 (-0.037 to 0.037)	0.73 (0.37 to 1.1)
Total terrestrial supply	1.94 (1.26 to 2.63)	0 (-0.15 to 0.15)	1.94 (1.11 to 2.78)

[1]WY1997-2010. Lower bound assumes bedload calculated 25 km upstream is reduced by sand mining and dredging. Upper bound assumes bedload calculated upstream passes through the 25 km reach to Mallard Island unchanged. On average, the net bedload at Mallard Island is assumed to net to be zero.

[2]Note, for small tributaries, all sediment deposited with or removed from flood control channels is assumed to be bedload with the balance being made up by suspended loads being deposited or removed (thus bedload supply can never be negative but in the Bay area is less than the amount of the sum of annual average removal and storage).

Sediment loads are sensitive to climate. Therefore, it is instructive to look at not just the average measured loads but also the predicted loads for a "climate normal" period, a period that is representative of the full range of climatic variation that can be experienced in the Bay Area and Central Valley. In the Bay Area, the 30-year period from 1981-2010 is used as a climate normal based on the convention of the Western Regional Climate Center (https://wrcc.dri.edu/). River discharges during this period are considered representative of a typical range of discharge conditions and the current water and land management regime that are currently experienced in the Bay Area. We used the hydrologic record for this period and the current rating curves for sediment mobilization to estimate "climate adjusted" annual average sediment loads. The resulting load estimates are the best estimate of mean annual sediment supply to San Francisco Bay from terrestrial sources under current average conditions (Table 4.2).

For Delta loads, the climate adjusted average suspended-sediment loads (0.58 Mt/yr) in Table 4.2 are lower than the average for WY 1995-2016 (0.73 Mt/yr). They are also lower than previous estimates for a normal water year during WY 1995-2002 (0.8 Mt/yr, Schoellhamer et al., 2005). The lower number is due to the WY 1995-2002 and WY 1995-2016 averages including years before the WY 1999 step decrease of SSC and lack of enough data to substantiate the step decrease in the early 2000s.

For the Bay Area small tributary watersheds the opposite is true. The climate adjusted average loads (1.38 Mt/yr) are slightly higher than the average for WY 1995-2016 (1.30 Mt/yr) and substantially higher than the normal water year estimates for WY 1995-2002 (0.9 Mt/yr, Schoellhamer et al., 2005). This analysis indicates that, under current conditions, tributaries will likely deliver a higher percentage of the total sediment load to the Bay (70%) than the WY 1995-2016 average (63%).

Table 4.2. Summary of estimated net mean annual suspended and bedload under present sediment erosion and transport conditions ("climate normal"). These loads are estimated assuming the WY 1981-2010 period of hydrology is representative of a typical range of discharge conditions and the current water and land management regime experienced in the Bay Area. For Mallard Island, the rating curve for the period including and after WY 1999 is assumed to be representative. No adjustment in the small tributaries ratings were made due to insufficient evidence of a change. Please see the methods section for details on error estimation methods.

	Suspended load (Mt/yr)	Bedload (Mt/yr)	Total load (Mt/yr)
Delta	0.58 (0.39 to 0.77)	0.025 (-0.07 to 0.12)	0.61 (0.32 to 0.89)
Bay Area Watersheds[1]	1.38 (0.91 to 1.85)	0.013 (-0.056 to 0.082)	1.39 (0.85 to 1.93)
Total net terrestrial supply	1.96 (1.30 to 2.62)	0.038 (-0.12 to 0.20)	2.0 (1.2 to 2.8)

[1]Assumes that the estimates of storage and removal by dredging practices in flood control channels remain valid and that all storage and removal is bedload.

In Table 4.1, the net bedload supply is estimated to be zero because the predicted supply of 111,000 t/yr (Table 3.6) is offset by an approximately equal amount of storage in and removal from flood control channels (Table 3.7). We currently estimate that flood control channels around the Bay store an annual average (net) of about 30,000 t/yr and flood control agencies on average remove about 82,000 t/yr (Table 3.7). The similarity of this estimate to the regional bedload estimate, although coincidental, probably somewhat reflects the likelihood that the majority of sediment stored and removed is coarse in nature (sands and gravels). Data on storage and removal, however, are lacking for many tributaries and are not being systematically (annually) collated for the region in any kind of regional database and the data that were collated by the FC 2.0 project (available at floodcontrol.sfei.org) were only collected to 2013.

While the total mass of bedload is small compared to the overall sediment supply, bedload is still an important resource to track. Bedload is typically dominated by coarse grain sizes. Coarse sediment supports beaches, can be used to support the development of an upland transition zone in wetland restoration projects, helps (along with suspended sediment) to attenuate wave energy on our mudflats in the face of sea level rise, and is extracted from the Bay as a resource for construction materials. In addition, bedload storage and removal from flood control channels can be very important at a local scale. Given this context, the uncertainties associated with the supply of coarse sediment and the coarse sediment budget for the Bay, improved understanding of supply, storage, and removal of coarse sediment from flood control channels is an important data gap.

What are the present temporal trends of fine and coarse sediment supply to San Francisco Bay?

Sediment Supply from the Delta

Since the step decrease in SSC in water year 1999, there has been no statistically significant trend in sediment supply from the Delta to the Bay. If there were an ongoing change in suspended-sediment supply from the Delta, it would appear as a change in slope on the double mass plot since WY 1999; there is no apparent change in slope. Recall that the slope is load divided by discharge which is the mean SSC shown on (Figure 3.1c). The determination of no significant trends from the double mass diagram is also confirmed by an analysis of changes in discharge, load, and suspended-sediment concentrations individually. The Spearman rho and Kendall tau tests evaluate whether a time series has a monotonic trend (Conover 1980, Helsel and Hirsch 1992). In general, discharge, load, and SSC individually since WY 1999 have a visually slight decreasing trend (Figure 3.1) that is not statistically significant ($p<0.05$, Table 4.3). Drought during much of the 2010s caused discharge to have the non-significant trend. For load, the Kendall tau test indicates a decreasing trend is not significant but the Spearman rho test indicates that there is a significant decreasing trend. The possibly decreasing trend in load is largely driven by decreasing discharge associated with the drought during the latter part of the study period. The double mass diagram trend analysis corrects for discharge, and thus, we consider it to be more appropriate than trend analysis of uncorrected load.

Table 4.3. Significance levels (p) of Kendall tau and Spearman rho tests for a monotonic trend for WY 1999-2016 annual discharge, load, and mean suspended-sediment concentration (Figure 3.1).

	p for Kendall tau test	p for Spearman rho test
Discharge	0.150	0.080
Load	0.069	0.044
SSC	0.096	0.084

The Sacramento-San Joaquin River Delta is between the Central Valley and the Bay and thus the trend in sediment supply from Central Valley Rivers to the Delta and the trend in Delta SSC can affect sediment supply to the Bay. Russo et al. (2013) found that storm intensity increased from 1890 to 2010 in the San Francisco Bay Area and part of the Central Valley. In the Sacramento Valley, however, the increase in sediment transport by more intense storms has been more than offset by higher air temperatures which reduce snowpack, peak discharges, and sediment loads (Stern et al., 2016). Schoellhamer et al. (2013) developed a quantitative conceptual model of how the estuary and watershed adjusted to hydraulic mining and dams and they concluded that further adjustment will be as steps that occur only during greater floods than previously experienced since hydraulic mining. Humans, however, are actively managing the system to try to prevent greater floods. Morgan-King et al. (writ. comm.) found that the rate of decline of sediment supply from the Sacramento River has slowed and is approaching a lower limit. In the Delta, Hestir et al. (2013) found that SSC declined from WY 1999-2010. Hestir et al. (2016) estimate that 21-70% of the declining turbidity trend from 1975 to 2008 is due to sediment trapping by invasive and expanding submerged aquatic vegetation.

While reduced peak discharges and invasive aquatic vegetation (IAV) act to decrease sediment supply to the Bay, ongoing sea level rise and declining wind speed may increase it. Sea level rise increases tidal action and SSC in the Delta (Achete et al. 2017) and decreases wind-wave resuspension and SSC in Suisun Bay (Ganju and Schoellhamer 2010). In addition, Bever et al. (in press) found that autumn wind speed in Suisun Bay declined from 1995 to 2015 which would decrease wind-wave resuspension and SSC in Suisun Bay. The result of sea level rise and declining wind speed is that more sediment exits the Delta on ebb tide and less sediment enters the Delta on flood tide with a net result of more sediment supply from the Delta to the Bay.

The extent to which increased sediment trapping by IAV, decreased wind speed, and sea level rise act to change the supply of sediment to San Francisco Bay is unknown.

While the interior Delta has had a statistically significant decline in SSC since 1999 (Hestir et al. 2013), at the boundary between the Delta and the Bay at Mallard Island, the SSC and load have had a nonsignificant declining trend since WY 1999 (Table 3.3, Figure 3.1). This may be explained if the effect of a new sediment sink such as IAV in the central Delta may be dissipated at the seaward boundary of the Delta at Mallard Island, and thus, not identifiable in the Mallard Island SSC time series. In addition, increased sediment export due to sea level rise may counter the processes that reduce sediment export. If the possibly declining trend is real, it may take years or decades of data to be able to pronounce that the trend is statistically significant.

In summary, in the years since WY1999, there has been no significant trend in sediment supply from the Delta. Several mechanisms act to increase or decrease sediment supply, but their net effect is not discernible.

Sediment Supply from Bay Area Watersheds

At this time, there is no evidence of a trend in sediment supply from small tributaries. The double mass plots (Figure 3.6) suggest a downward trend for the most recent period; however, the data generally only cover a short length of time and have gaps that are years or decades long. With the sparse and incomplete datasets, it was not possible to isolate real trends from the effects of land use changes in Bay Area watersheds and the strong influence of variable climate on erosion in the tectonically active coastal area of California. A more sophisticated trend analysis is needed. The following paragraphs outline some of the factors that need to be considered: changes in climate; changes in land use; and changes in discharge that differ from changes in erosion.

Climate and erosion are intimately linked. Since smaller tributaries around the Bay Area exhibit very great rainfall and discharge variability (and much greater than the variability observed in the Central Valley), they are very sensitive to climatic conditions causing variable sediment erosion. Indeed, the supply processes during wet years and wet periods lasting 3-7 years in the coastal ranges of California are driven by mass wasting (landslides, debris flows, mud flows) that do not occur during dry years (Inman and Jenkins, 1999; McKee et al., 2003; McKee et al., 2013; SFEI-ASC, 2017). Thus, it is very important to measure trends using either a sufficiently long data set to capture these erosional sequences or to compare periods of similar climate (wet periods or dry periods) over long time periods (at least several decades). It is quite plausible (we cannot rule out) that the decreased small tributary loads and discharge-weighted mean concentrations in the recent years (shown by the double mass plots) are due to climate. Therefore, we suggest caution should be exercised when using the currently available data to forecast future sediment loads until another series of wet years have been observed.

Trends analysis for sediment loads from Bay Area tributaries is not a new endeavor. An attempt to discuss trends in small tributaries was previously made by McKee et al (2013). They focused on looking for trends in loads and yields in Cull Creek, San Lorenzo Creek, Alameda Creek, Guadalupe River, and Colma Creek. They argued that evidence was inconclusive except for Guadalupe and Colma Creek where there have been trends that could be directly related to known erosion problems associated with urban development (Schoellhamer, 2011; McKee et al., 2013). We speculate that if data collection was to resume, a similar decrease might be observed in the future for Zone 6 Line B in Fremont, which exhibited very high loads and yields during a short data collection period in WYs 2000- 2002 that may have been a result of urban development in that watershed. To avoid these trends associated with land use change and non-stationarity the analysis of loads prepared for this current report does not use the early period data for Guadalupe River and Colma Creek, either in the watershed specific regressions or in the Peninsula/South Bay sub-region regression. In addition, the data from Zone 6 Line B was kept separated from the East Bay province sub-region regression.

Population in the nine-county Bay Area increased from 2.681 million in 1950 to 7.151 million in 2010 (U. S.2010 Census, https://www.census.gov/2010census/). Initially this population increase was taken up by expansion of the urban area along the East Bay and Peninsula cities and in San Jose with increasing build out of slopes in excess of 5% on the surrounding hills. This period mostly occurred prior to the Clean Water Act and was mostly not accompanied by erosion control practice. There were many slope failures and sediment production was likely very high, and increased discharges from impervious areas lead to creek incision and further sediment production. Since that time, although there are still landslides during very wet years, city and county agencies have done a lot of work to stabilize slopes and creek channels. Today, in most cases, sediment production in near- field areas around the Bay has likely stabilized and the occurrence of landslides is less frequent.

More recently, with buildout of available space largely complete around the ring of the Bay, population has been expanding in the outer lying areas. Examples include Morgan Hill in Coyote Creek watershed, the middle and upper Napa and Sonoma valleys, and most notably, the Dublin, Livermore, Pleasanton, and San Ramon areas of Alameda County (mostly within the Alameda Creek Watershed) and the Clayton, Pittsburg, Brentwood, Oakley, and Antioch areas of Contra Costa County (all of which have had a doubling of population in the 30 years since 1980). The land use changes in these areas have occurred mostly on flatter land (except San Ramon and Clayton), after the Clean Water Act, and with modern erosion control and drainage practices that help to reduce the sediment production during development. However, increased discharges still occur due to impervious surfaces and these may not carry much of an increased load, the net result being the possibility of decreased suspended-sediment concentrations.

It is these factors (climate change, land use, and discharge production), along with climatic fluctuations, that need to be considered in a small tributaries trends analysis. Since Sonoma Creek, Napa River, Walnut Creek, Alameda Creek, and Guadalupe River all have historic data sets, these appear to be the best place to make such an effort. We suggest, that the methods described by Warrick (2015) could be used for a trend analysis because they account for changes in discharge, concentrations and loads as they relate to real causative influences including climate cycles and changes to land use and water management. So at this time, we are unable to conclude there has been a trend in sediment supply from Bay Area small tributaries due to spatial heterogeneity and the strong influence climate on erosion. But as described above, trends for individual watersheds have been noted. Therefore, with further carefully designed data collection and appropriate use of statistical methods, it will likely be possible in the future to see further trends for individual watersheds and perhaps, with the aid of modeling, it may even be possible to make statements of trends at the regional scale.

Sediment Transport Between Subembayments

Suisun Bay is erosional and the erosion rate is decreasing so it is likely to be approaching a state of dynamic equilibrium, meaning that there is no net change on a decadal time scale but net erosion or deposition occurs on an annual time scale. Over the 15 years of data WY 2002-2016, Suisun Bay was net depositional (Figure 3.7). Sediment is exported during wet years and imported during dry years. WY 2012-2016 were dry, so the period of record ends with a prolonged dry period and net sediment deposition. High discharges in WY 2006 exported about 11 Mt of sediment. Thus the higher discharges of WY 2017 likely exported a greater quantity of sediment and the sediment deposited from WY 2002-2016 was likely removed and the WY 2002-2017 period was likely erosional. Erosion would be consistent with our estimate of mean annual long- term erosion under current conditions. This erosional rate (0.87 cm/yr) is smaller than observed 1942-1990 (1.2 cm/yr) and has been decreasing since the early 20th century (Figure 4.2), which indicates that Suisun Bay is approaching dynamic equilibrium.

Unfortunately, a similar exercise cannot be performed for the Lower South Bay. Suspended-sediment flux data at the Dumbarton Bridge are not available over a long enough period to evaluate trends in transport. Given a 50-year plan for wetland restoration, evidence of contamination of both PCBs and Hg, challenges associated with algal productivity, and the overall linkage of sediment dynamics to these issues, we recommend further data collection to help support a better understanding of fluxes in the Lower South Bay.

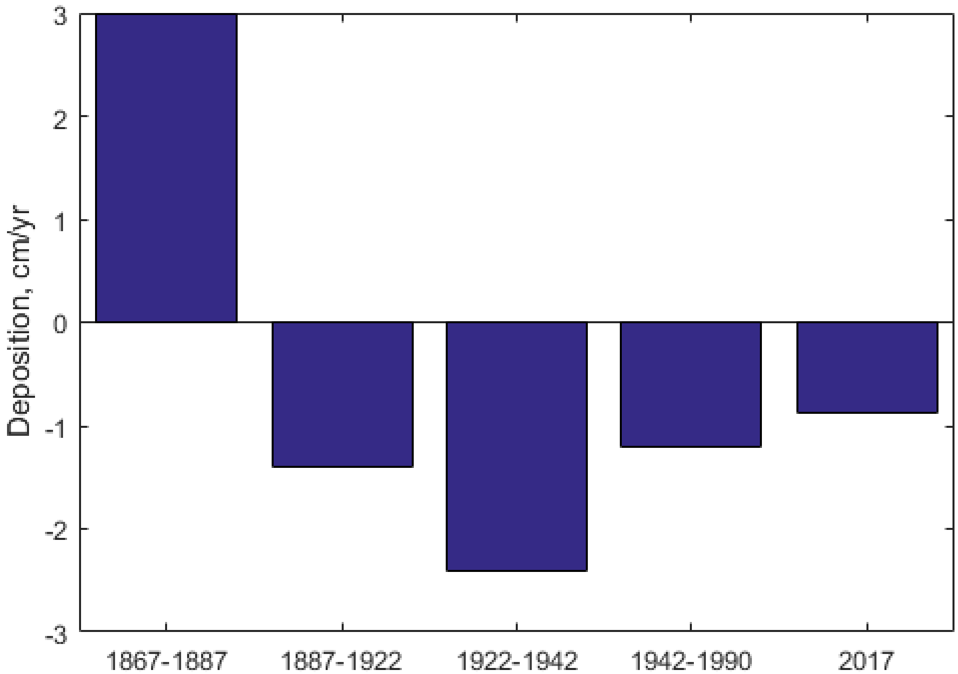


Figure 4.2. Suisun Bay deposition. 1867-1990 data are from Cappiella et al. (1999). Negative values indicate erosion. The negative value labeled as “2017” is our estimate of mean annual long-term erosion under current conditions (0.87 cm/yr). It is not the measured value for WY2017. The long-term estimate is based on the mean annual Delta outflow for WY 1981-2010 (22,800 Mm^3), the mean annual long-term deposition rate of Suisun Bay under current conditions (-1.26 Mt/yr, which is erosional, see Table 3.9), the surface area of Suisun Bay (165 Mm^2), and assuming a bulk density of 850 kg/m^3 (Porterfield 1980).

What are scenarios for future sediment supply to San Francisco Bay?

Sediment Supply from the Delta

Previous landscape scale changes in the estuary and surrounding watershed over the past 200 years caused average annual sediment supply to San Francisco Bay to vary by an order of magnitude or more (Gilbert 1917, Schoellhamer 2011). Major past changes that increased sediment supply include hydraulic mining in the Sierra Nevada and widespread land use changes including deforestation, land reclamation for agriculture, urbanization, flood control, and water storage. Major past changes that decreased sediment supply include dam construction and the passing of the hydraulic mining sediment pulse, which combined to shift sediment dynamics from transport- to supply-limited conditions. Since intensive dam construction began in the 1930s, the largest floods resulted in net sediment export and caused “step” decreases in suspended-sediment concentration of 29-41% (Schoellhamer, 2011, Hestir et al. 2013).

The net effect of several changes that are currently taking place, and will continue into the future, are uncertain but appear likely to produce little net change in present sediment supply (Figure 3.1c). If IAV continues to expand and if wind speed continues to decrease, they would both act to reduce sediment supply to the Bay. The effect of these mechanisms is countered by sea level rise which increases tidal action and sediment suspension in the Delta (Achete et al. 2017) and decreases wind wave resuspension in Suisun Bay (Ganju and Schoellhamer 2010). Achete et al. (2017) simulated a sea level rise scenario for the Delta and found sediment export would increase 10% in 2100. In addition, Stern et al. (writ. comm.) simulated the response of the Sacramento River watershed to future climate scenarios and found that increasing storm intensity will have a greater effect on sediment transport than warmer temperatures, so sediment transport will increase if the supply of erodible sediment in the watershed remains constant.

Foreseeable sudden and drastic changes have a low probability of greatly altering sediment transport. A flood larger than experienced since hydraulic mining could cause additional geomorphic adjustment that previously has led to step decreases in SSC (Schoellhamer et al. 2013). Humans, however, actively try to prevent such a flood from occurring, and as mentioned earlier, about 48% of the Central Valley watershed is upstream from dams designed for water supply that capture, delay, and diminish discharge from spring snowmelt and inadvertently eliminate or damp many of the peak discharges that are normally crucial for sediment transport. Almost all medium sized events (~2–10-year return interval discharges) that once constituted a range of ‘dominant discharges’ for sediment transport are now absorbed by the many dams (see for example Kondolf and Matthews, 1991). Another possibility is increased trapping of sediment due to permanent flooding of some Delta islands, possibly after a large earthquake. Achete et al. (2017) simulated flooding of the four most vulnerable islands and found that sediment export decreased 15%. The proposed use of tunnels to divert Sacramento River water to export pumps in the southern Delta is predicted to decrease downstream sediment supply to San Francisco Bay 8-9% (p.5.3-24, CDWR 2013). In terms of present day supply this change may be significant but it is small compared to changes since 1850 caused by hydraulic mining and reservoirs.

Because ongoing changes associated with climate change and invasive species do not appear to be significantly affecting net sediment supply at present, and foreseeable sudden and rapid landscape changes are unlikely to do so, we hypothesize that future changes in sediment supply will be much smaller than those observed since 1850. For example, deposition in Suisun Bay (Figure 3.7) was large after hydraulic mining and was followed by large erosion of those deposits. The rate of erosion has since been decreasing as the Bay becomes more stable and this stability compared to the late 19th and early 20th century is expected to continue. A record flood, however, has the potential to greatly alter sediment supply.

To date, efforts assessing future sediment dynamics in the Delta and net export to the Bay have been focused on assessing the impact of a single or a few key factors. This approach is common in quantitative analyses as it allows for a robust treatment of the variables considered.

Subsequent analyses should focus on building on previous studies and synthesize all key factors driving sediment dynamics, such as land management, climatic, and ecological factors, to determine the likely range of expected sediment outcomes for realistic future landscape scenarios in the Delta.

Sediment Supply from Bay Area Watersheds

Forecasting will be essential for assessing future sediment supply to the Bay from the small tributaries**.** The analysis provided in this report indicates that existing monitoring data are not sufficient for assessing trends in average annual sediment supply to the Bay over the past several decades. Future changes in sediment supply to San Francisco Bay from the surrounding watersheds will be highly dependent on shifts in precipitation and air temperature associated with a changing climate. Recent efforts focused on downscaling climate model outputs for use in the Bay Area show similarity with respect to longer, drier summers in the future (Flint and Flint 2012) but differing precipitation dynamics ranging from much wetter to much drier than current conditions (Micheli et al. 2012). A wetter future with more frequent extreme precipitation events would result in more frequent hillslope mass failures and higher flood discharges that would cause increased sediment transport and channel erosion in many Bay Area creeks. These processes could lead to an increased average annual sediment supply to the Bay, as well as an increase in the magnitude of sediment pulses that are delivered during commonly occurring "bankfull" floods (i.e., floods with a return interval of 1.5 to 2 years). In addition, longer, drier summers could lead to shifts in vegetation assemblages towards smaller, sparser vegetation stands on hillslopes and in riparian areas, which could increase erosion and overall sediment delivery during storm events. Conversely, a drier future with less frequent large precipitation events would result in less large flood pulses but could result in similar if not a higher average annual sediment supply to the Bay compared to current conditions. Flood pulses could contain more sediment than they would under current conditions due to vegetation shifts affecting erosion rates. In addition, a future with smaller flood pulses that happen very frequently could deliver a considerable amount of sediment to the Bay over the long-term.

The *Healthy Watersheds Resilient Baylands* project is a recently-initiated regional effort that will help address this need. The project will address future sediment supply dynamics by focusing on the range of likely changes to average annual watershed sediment supply based on downscaled climate model outputs (i. e., what's the difference in supply between the driest and wettest future conditions?), and the range of likely changes to the frequency of large storm pulses that deliver watershed sediment to the Bay (i. e., what's the difference in 2-year to 100- year flood discharge between the driest and wettest future conditions?). The results will provide as a starting point to help determine how different the future sediment supply will be compared to what the Bay has received over the past several decades.

How can sediment monitoring be improved to fill data gaps and better provide information for resource managers?

Before implementing a large-scale potentially expensive sediment monitoring program, the first step would be to lay out the data collection objectives starting with the management questions. Once the management questions are developed and reviewed, these could then be the basis for conceptual model development followed by projects designed to answer the management questions with existing data. Any questions remaining unanswered by these initial projects could then form the basis of the design of a sediment monitoring program. Here we lay out suggested data improvements based on our preliminary understanding the general suite of management questions. However, these questions have not yet been formally reviewed or prioritized. This is the charge of the RMP Sediment Workgroup that has been recently formed.

Large River Supply from the Central Valley

Suspended-sediment supply from the Sacramento and San Joaquin Rivers above the head of tide is very well quantified and those measurements should continue. The Delta traps suspended-sediment so the supply to the Bay is less. Suspended-sediment supply at Mallard Island is the largest single terrestrial supply number in our calculations. Continuous time-series of turbidity data, review and editing of those time series, and collection of water samples for SSC are necessary to produce a time series of SSC. The method for estimating suspended-sediment load from SSC is well established (McKee et al. 2006) but it is based on detailed data collected in the 1990s prior to the 1999 step decrease in SSC. Ideally more detailed data would be collected to verify or update the procedure to estimate suspended-sediment load from SSC within the 950 m wide cross-section at Mallard Island.

Bed-load measurements in the vicinity of Mallard Island would help resolve the effect of sand mining and dredging on bed load supply to the Bay. The likely bounds of bedload of coarser material at Mallard Island is estimated by calculating bedload at gaging 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. Continuous collection of water velocity data at Mallard Island in coordination with detailed tidal measurements of velocity, bed-material size, and bedload in the cross section would likely provide an improved method for estimating supply of bedload to San Francisco Bay at Mallard Island. Acoustic measurements of bedforms and motion of bedforms is an alternate method of 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 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 suspended supply, the coarse sediment has an out-weighted importance in the context of sea-level rise challenges, beach nourishment, wave energy dispersion, and the future of sand mining in the Bay.

Small Tributaries Supply from the Nine Bay Area Counties

Given climate within the Bay Area is different in the north, east, and south where the largest watersheds are found, it is important to have a network of monitoring stations in the Bay Area that are spatially distributed; several in each county on the larger tributaries would be a good starting point for consideration. Generally, loads for small tributaries are moderately well quantified for suspended fine fractions at the regional scale although there are some weaknesses for some key tributaries. Data collection that is presently operating should be continued if monitoring trends is a high priority and for providing data to understand the potential for large storms to trigger mass wasting processes such as landslides, debris flows and mudflows which, when they occur, can have multi-year effects on sediment loads. Existing sites are:

- Alameda Ck. At Niles (Suspended and bedload)
- San Lorenzo Ck. At San Lorenzo (Suspended load)
- Guadalupe R. Above Highway 101 At San Jose (Suspended load)

Recommendations for an expanded program are:

- **North Bay:** Sonoma Creek and Napa River in the North Bay are large watersheds with high suspended-sediment loads but the data for both systems were collected in the 1960s and 1970s and are weakest for Napa. Despite recent efforts to quantify sediment yields for the Napa and Sonoma sediment TMDLs (SFBRWQCB, 2008; 2009), these watersheds need further sampling to help verify or refute the historic rating curves. Presently the computations made from the historic data must be considered uncertain. Yet collectively, as described earlier, these two tributaries supply, on average, 23% of the load from the collective small tributaries and during some years can supply 45% of the total small tributary load despite only comprising 12% of the total land area of small tributaries (8045 km^2 or 3,106 mi^2). Bedload data are lacking completely for Sonoma Creek and are very limited for the Napa River. As discussed above, since bed loads that potentially come into the Bay from the Central Valley may be completely damped by management practices in the lower Delta, and given the out-weighted importance of coarse sediment supply, the uncertainty associated with bed load information in the Napa and Sonoma watersheds should be given strong consideration. Once collected, suspended-sediment and bed-load data from these key watersheds would be a very important component of a larger data set to support the calibration of a dynamic simulation model. Once calibrated, this model could be used to explore past and future regional scale sediment loading trends.
- **East Bay:** Data are most lacking in Walnut Creek. Again, the rating curves are based on historic data and need verifying. Walnut Creek is estimated to supply 9% of the suspended-sediment load and 20% of the annual bed load from the collective small tributaries. Yet modern data on suspended-sediment loads are lacking to verify the rating curves and estimates of bedload were based on model calibration for that system with only sparse historical data to support the calibration. Walnut Creek, along with Napa River, Sonoma Creek and Alameda Creek are estimated to deliver an average of 45% of the suspended load to the Bay from small tributaries that drain the nine-county Bay Area collectively despite being only 37% of the land area. These watersheds should be considered as anchor watersheds for any additional data collection.
- **Peninsula/ South Bay:** Data are lacking for wetter years on Coyote Creek to define the upper part of the sediment rating curve, San Francisquito and Colma are lacking modern data to verify

the sediment ratings. These three Creeks are very important as they are estimated to supply 55,500 metric t (4.3%) of the total sediment load from the collective small tributaries overall, 25% of the estimated sediment supply to the South Bay from Santa Clara and San Mateo counties and, along with Guadalupe River and Alameda Creek (both relatively well-sampled), the majority of the sediment supply to the southern portions of San Francisco Bay. Bedload data are lacking on all three of these tributaries. Although these are still smaller loads compared to the North Bay watersheds and yields of both water and sediment are much lower in the South Bay compared to the tributaries of Marin, Sonoma and Napa, sediment supplied by these creeks, although less important for the Bay sediment budget as a whole, is important for local South Bay marshes. In this context, even low yielding rivers and creeks of the South Bay are likely very important from a management perspective.

The accurate quantification of suspended loads is challenging logistically, but can be improved by the use of turbidity as a surrogate (as is the case at all three of the currently operating suspended-sediment gauging locations). The ideal sampling location for an expanded data collection program would be to sample watersheds at a location that is as close to the Bay as possible but still non-tidal and where there is an existing overhead structure (preferably, a road bridge with a 2m wide foot path on the upstream side). However, given that all of these watersheds have historic data collection, reoccupation of historic sites is preferable for trends analysis and for supporting the development of a dynamic simulation model for estimating sediment loads from small tributaries to the Bay.

Bedload data collection is even more challenging and, unlike suspend sediment load where deployment of a remotely sensing turbidity probe can be used as a surrogate, there are no surrogate measures available. Bed sediment loads are generally poorly quantified because of two issues. Firstly, there are a lack of sites both historical and presently operating. Secondly, even when operating, the existing data sets mostly lack data at the upper end of the discharges for each site due to the difficulty in getting the equipment to behave properly on the bed in discharges above about 10 ft/s. Thus, bedload measurements are not always logistically possible, which may indeed be the case for San Lorenzo Creek, where the trapezoidal flood channel may transport much of its discharge at high velocities. The logistical challenges for bedload can be resolved in three possible ways:

1. The discharge of water and sediment can be quantified with an Acoustic Doppler Current Profiler (ADCP) (Ruhl and DeRose, 2004; Kosaschuk et al., 2005; Rennie et al., 2007). An ADCP measures three dimensional velocity profiles using the principle of Doppler shift whereby the spectrum of sound reflected back to the instrument from the water column is shifted by a magnitude related to velocity. The bottom tracking function and the acoustic backscatterance can be used to estimate bedload and suspended-sediment concentrations. These instruments can be deployed in both non-tidal and tidally influenced settings. Deployment upstream from the head of tide would provide data on bedload entering the tidal channel. Deployment at the mouth of a tributary is

more difficult due to tides but provides data where the tributary discharges to the open waters of the Bay.

2. More limited data could be collected during low to moderate discharge conditions and used to calibrate bed load equations for each specific system. Methods have been developed for gravel bed systems (Wilcock, 2001) which could be adapted for use in the Bay Area to extend the limited records derived from the deployment of a conventional "Helley-Smith sampler"
3. The development of a dynamic simulation model for the Bay Area for making future estimates of suspended loads, bed loads, and the sediment trapping capacity of flood control channels.

A full review of these instruments and methods, and their costs, and a comparative analysis of other options (such as deploying a turbidity probe equipped with wiper) is beyond the scope of this report but could be considered as an initial step in the design of an expanded sampling program for small tributaries.

Channel storage and removal data are important but are lacking or challenged by data quality. During some years, the amount of net storage and removal is of a similar magnitude to fluvial supply to the Bay from the small tributaries collectively. Channels preferentially store coarse sediment which has high value in relation to beach nourishment, wave attenuation, and other measures to accommodate sea level rise. It is also of value in terms of a resource for building materials. The following bullets highlight recommendations for improving the quality of data for channel storage and removal volumes.

- Data on sediment removal from flood control channels has been compiled through the FC 2.0 project up to WY 2013 but is lacking for later years. There is no systematic process of data collation in place and presently agencies are not collecting grain size information. In addition, methods of qualification are not standardized. Future data collection and collation should include sediment removed from both fluvial and tidal portion of flood control channels.
- Net channel storage data are even more scarce. There are few channels with a systematic method of regular capture of suitable cross-section and long profile data in place and there is presently no mechanism for regularly capturing and collating these data for regional use. Methods of qualification are not standardized.
- The small tributary estimates in this study are for sediment delivery to the head of tide. A substantial portion of this sediment can be trapped in the tidal channel that connects the tributary to the Bay and the tidal channel can trap sediment from the Bay (Downing-Kunz and Schoellhamer 2013, 2015; Shellenbarger et al., 2015). To determine deposition in the tidal channel, the quantity of sediment from the Bay that is trapped in the tidal channel, or sediment supply to the open waters of the Bay, a sediment budgets for the tidal channels are needed. This would complement data collection on sediment removal in tidal portions of flood control channels by flood control agencies.

- Presently the conversion factor between volumetric measurements and mass units is poorly quantified both for sediment stored in, and removed from, fluvial and tidal portions of flood control channels. A small regional study could be completed to increase accuracy. Improved mass density data are also needed for comparing net sediment supplies from the tributaries the accommodation space in the Bay. Differences and inaccuracies in the mass density used for each will result in quite different estimates of the net deficit. Thus, a study of mass density of Bay sediments is also needed.

Sediment Transport between Subembayments

San Francisco Bay is composed of several connected subembayments that differ in terms of terrestrial sediment supply, freshwater inflow, bathymetry, and ocean connectivity. Suspended-sediment transport between Bay segments is difficult to estimate because of large cross sections and tides that produce spatial and temporal variability that must be considered. Continuous monitoring of SSC, water velocity, and water level and discrete measurements of water discharge and cross-sectional SSC are needed to calculate suspended-sediment flux. Despite the difficulties and associated relatively large error, the estimates at Dumbarton and Benicia Bridges provide useful information on sediment transport, sediment supply for restoration projects, and the geomorphic condition of the estuary. In addition, transport and loading of sediment-associated constituents can be calculated from suspended-sediment flux. Beginning in 2018, additional data collection at Dumbarton Bridge will evaluate proposed corrections to previously collected suspended-sediment flux data for tidally-asymmetric flocculation and reduce uncertainty in future measurements. In addition, sediment monitoring including a new bathymetric survey and sediment transport modeling for the far south Bay has been conducted by USGS as part of the South Bay Salt Pond Restoration Project. Sediment flux at Benicia Bridge is estimated from surrogate relations developed from data collected 15 years ago. Continuous flux monitoring there would provide more robust estimates used to calculate the sediment budget for Suisun Bay. Another alternative would be to collect and analyze data to check and improve the surrogate relations.

Bridges are typically built as short as possible to save money and thus are located at constrictions between subembayments with a relatively small cross section which are also the best places to measure suspended-sediment flux. Measurements at Carquinez Bridge would provide estimates of sediment transport at the eastern boundary of San Pablo Bay. Coupling these estimates with those from Benicia Bridge, a sediment budget for Carquinez Strait could be developed.

Measurements at Richmond Bridge would provide estimates of sediment transport at the western boundary of San Pablo Bay. If done in conjunction with measurements at Carquinez Bridge, a sediment budget for San Pablo Bay could be developed. This is a large cross section at which measurements at multiple points or measurements in conjunction with a numerical model (discussed below) may be necessary.

For estimating the sediment budget of all of San Francisco Bay, sediment flux at the Golden Gate is a large and unknown data gap. Tidal cycle measurements collected during high freshwater discharges in WY 2016 (funded by the San Francisco Estuary Partnership and RMP) and WY 2017 (funded by RMP) are being evaluated by the USGS California Water Science Center. A report is expected by the end of 2017. Large tidal currents, ocean swell, wind, and the largest cross- sectional area are additional confounding factors at the Golden Gate.

Measurements at the Bay Bridge would provide estimates of sediment transport at the northern boundary of South San Francisco Bay. Similar to Richmond and the Golden Gate, measurements at multiple points or measurements in conjunction with a numerical model (discussed below) may be necessary.

Confounding factors in calculating suspended-sediment flux include the difficulty of considering spatial variation of depth, velocity, and SSC in the large cross section. A calibrated three-dimensional model includes cross-sectional variability and be used to relate collectible data such as point SSC and point velocity to suspended-sediment flux. The combination of a model and measurements can be used to develop surrogate relations for sediment transport, similar to those used at Mallard Island and Benicia Bridge, enabling long-term collection of the less costly surrogate data. The model should be calibrated to point velocity, point SSC, and discrete measurements of water discharge and suspended-sediment flux in the cross section. Such a model would also be useful for calculating sediment supply from the Estuary to specific locations, tidal marshes, and tidal marsh restoration sites to help evaluate sustainability of existing tidal marsh and feasibility of marsh restoration as sea level rises.

Adding sediment flux monitoring at the Carquinez, Richmond, or Bay Bridges would be a major effort and expense. The need for this expense depends on the management questions. Therefore, managers should carefully consider if there is a compelling need for information on mass balances for the Carquinez Straits, San Pablo Bay, and Central Bay. Flux monitoring at the Golden Gate Bridge is needed regardless to close the overall mass balance for the Bay, but this type of monitoring is extremely challenging and costly.

Other Topics for a Comprehensive Sediment Monitoring Strategy

The recommendations from this report are focused on improving the monitoring for sediment supply to the Bay from the Delta and small tributaries. A more comprehensive strategy will be developed for the *Healthy Watersheds-Resilient Baylands* Project. This strategy should consider a broader array of topics, such as:

- **Data Analysis Methods**. In order to convert sediment supply data into useful information, standardized methods are needed to calculate the loads and to conduct trend analysis. In particular, methods are needed for more thorough trend analysis that takes into account both climatic fluctuations and land-use change.

- **Modeling**. Sediment loads from all small tributaries currently have to be inferred from data in representative watersheds using simple algebra and regression statistics. Dynamic simulation models would improve the efficiency of future estimates for ungaged streams and for simulating changes in hydrology due to land use and climate change. Similarly, understanding the movement of sediment between different segments of the Bay would require mechanistic sediment transport models combined with the observations at the bridges spanning the Bay.
- **Shoreline Resilience Monitoring**. One of the critical management questions regarding sediment supply is whether marshes are being inundated given the net effect of sea level rise, beneficial reuse of sediment, and restoration projects. A robust sediment monitoring strategy should have a component to monitor this outcome directly using sediment elevation tables and other tools. The shoreline resilience calculations that will be completed for the *Healthy Watersheds-Resilient Baylands* Project will inform this part of the monitoring strategy.
- **Sediment Provenance Studies.** The provenance of sediment depositing in marshes could be considered directly by the use of isotopic or mineralogical provenance techniques. For example, the source of sediment depositing in South Bay salt ponds that have been restored to tidal action and other tidal restoration projects is unknown. An analysis of the mineralogy and chemistry of deposits within restoration sites, morphologic elements of the Bay and source sediments in the Central Valley and local tributary watersheds can be used to estimate the contribution from different sources. Gaining this knowledge would add a lot of confidence to answering the question – is there enough sediment for restoration and maintenance of existing mudflats, marshes and shorelines? Sediment provenance studies could also be designed to address other management questions such as those related to sources and fate of sediment-associated contaminants, optimal open water placement of dredged material for beneficial reuse, and source of sediment deposits in flood control channels.

Recommended Framework for Prioritizing Monitoring Recommendations

Continued monitoring and evaluation of monitoring data would 1) provide additional data to improve the supply estimates in this report by improving consideration of water year variability and 2) observe changes in sediment supply due to changes in climate and land use including habitat restoration and fires. Ideally, monitoring efforts that measure large sources of sediment at a low cost should be prioritized. A qualitative diagram of our estimates of cost versus magnitude of some monitoring efforts is shown in Figure 4.3. If the objective is to improve a local estimate, such as for a restoration project at the margin of the estuary, sediment supply from the local watershed, even if small, and quantification of supply from the estuary should be prioritized.

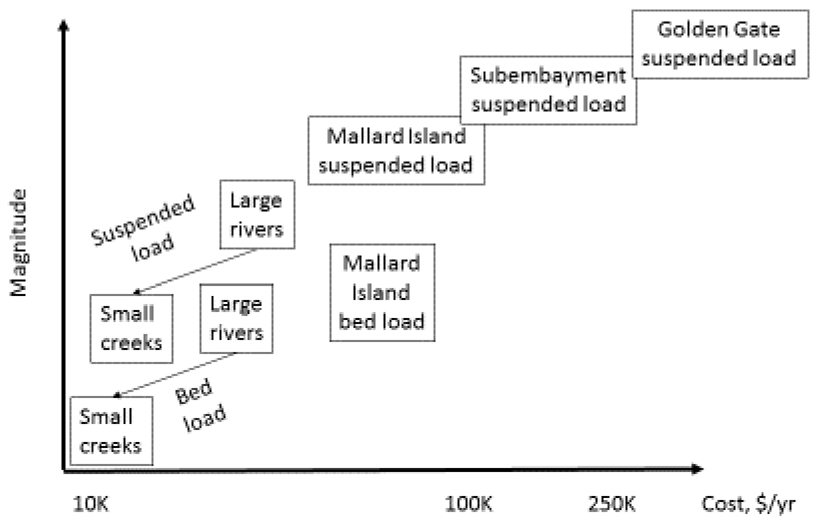


Figure 4.3. Relative magnitudes of sources of sediment and estimated operating costs of selected monitoring activities. Does not include installation costs.

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6. Appendix

Table 6.1. Bedload sediment data (US short tons) measured by the USGS in small tributaries in the nine-county Bay Area. Note, San Lorenzo River at Big Trees and Uvas Creek in Santa Cruz County are not tributaries to the Bay but are included to increase dataset size.

	Alameda Ck. At Niles	Arroyo De La Laguna Near Pleasan-ton	Alameda Ck. Below Welch Ck. Near Sunol	San Lorenzo Ck. At San Lorenzo	Cull Ck. Above Cull Ck. Reservoir Near Castro Valley	San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley	Crow Creek Near Hayward	Zone 6 Line B At Warm Springs Boulevard At Fremont	Wildcat Ck. At Vale Road At Richmond	Corte Madera Ck. Near Ross	Napa R. Near Napa	Uvas Ck. Above Uvas Reservoir Near Morgan Hill	San Lorenzo River at Big Trees	Guadalupe R. Above Highway 101 At San Jose	West Fork Permanente Ck. Near Monte Vista
USGS gage	11179000	11177000	11173575	11181040	11180960	11180825	11180900	11172365	11181390	11460000	11458000	11153900	11160500	11169025	11166578
Drainage Area (sq. mi.)	633	405	145	44.8	5.79	18.0	10.5	0.830	7.72	18.1	218	21.0	106	160	3.09
Water Year	East Bay									North Bay		Peninsula/ South Bay			
1973												650	14,827		
1974												1,067	11,675		
1975												228	6,108		
1976												0	104		
1977													8.0		
1978									462	4,172	6,710		13,624		
1979					1,636				179	313			722		
1980					13				1,689	1,641			4,120		
1981					2,651	126							4,435		
1982													105,617		
1983					172	1,675									
1984					82	127									
1985					1,084	32									
1986					43	493									1,285
1987					1.0	33									
1988					1.0	11									
1989						4.0									

	Alameda Ck. At Niles	Arroyo De La Laguna Near Pleasan-ton	Alameda Ck. Below Welch Ck. Near Sunol	San Lorenzo Ck. At San Lorenzo	Cull Ck. Above Cull Ck. Reservoir Near Castro Valley	San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley	Crow Creek Near Hayward	Zone 6 Line B At Warm Springs Boulevard At Fremont	Wildcat Ck. At Vale Road At Richmond	Corte Madera Ck. Near Ross	Napa R. Near Napa	Uvas Ck. Above Uvas Reservoir Near Morgan Hill	San Lorenzo River at Big Trees	Guadalupe R. Above Highway 101 At San Jose	West Fork Permanente Ck. Near Monte Vista
USGS gage	11179000	11177000	11173575	11181040	11180960	11180825	11180900	11172365	11181390	11460000	11458000	11153900	11160500	11169025	11166578
Drainage Area (sq. mi.)	633	405	145	44.8	5.79	18.0	10.5	0.830	7.72	18.1	218	21.0	106	160	3.09
Water Year	East Bay									North Bay		Peninsula/ South Bay			
1990				28	71	9.0									
1991				73	36	27									
1992				544	1,780	80									
1993				751	136	451									
1994					1,932	7.0									
1995					1,310										
1996					273										
1997					2,336										
1998					736	892									
1999					993	168									
2000	5,149	16,004	1,939		50	465	1,901	6,029							
2001	247	3,020	5.0		391	131	38	18,797							
2002	1,273	6,144	269		482	275	630	2,223							
2003		15,287	222		11,261	157	1,100								
2004															
2005	16,123													1,663	
2006	16,408														
2007	2,906		169												
2008	4,633		182												
2009	3,252		289												
2010	8,139		117												
2011	22,850		10,588												

	Alameda Ck. At Niles	Arroyo De La Laguna Near Pleasan-ton	Alameda Ck. Below Welch Ck. Near Sunol	San Lorenzo Ck. At San Lorenzo	Cull Ck. Above Cull Ck. Reservoir Near Castro Valley	San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley	Crow Creek Near Hayward	Zone 6 Line B At Warm Springs Boulevard At Fremont	Wildcat Ck. At Vale Road At Richmond	Corte Madera Ck. Near Ross	Napa R. Near Napa	Uvas Ck. Above Uvas Reservoir Near Morgan Hill	San Lorenzo River at Big Trees	Guadalupe R. Above Highway 101 At San Jose	West Fork Permanente Ck. Near Monte Vista
USGS gage	11179000	11177000	11173575	11181040	11180960	11180825	11180900	11172365	11181390	11460000	11458000	11153900	11160500	11169025	11166578
Drainage Area (sq. mi.)	633	405	145	44.8	5.79	18.0	10.5	0.830	7.72	18.1	218	21.0	106	160	3.09
Water Year	East Bay									North Bay		Peninsula/ South Bay			
2012	1,931		628												
2013	7,046		214												
2014	175														
2015	4,417														
2016	8,586														
Count	15	4	11	4	23	19	4	3	3	3	1	4	10	1	1