Water Availability and Use Science Program

Prepared in cooperation with the San Francisco Estuary Institute Aquatic Science Center, the California State Coastal Conservancy, and the San Francisco Bay Conservation and Development Commission

Sand Supply to San Francisco Bay from the Sacramento and San Joaquin Rivers of the Central Valley, California

Open-File Report 2024–1055

U.S. Department of the Interior
U.S. Geological Survey

Cover. Boardwalk leading out to Mallard Island streamgage with water and tule plants.
Photograph by David Hart, U.S. Geological Survey, October 2018.

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Contents

Figures

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
Volume		
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
million cubic meters (Mm^3)	810.7	acre-foot (acre-ft)
Mass		
metric ton (t)	1.102	ton, short (2,000 lb)
metric ton (t)	0.9842	ton, long (2,240 lb)
Mass rate		
million metric tons per year (Mt/yr)	1,102,000	tons, short (2,000 lb) per year
Flow rate		
cubic meter per second (m^3/s)	35.315	Cubic foot per second (ft^3/s)
Density		
metric tons per cubic meter (t/m^3)	62.428	pounds per cubic foot (lb/ft^3)
kilogram per cubic meter (kg/m^3)	0.0624	pounds per cubic foot (lb/ft^3)

Datum

Coordinate information is referenced to the North American Datum of 1983.

Supplemental Information

In this report, bedload sediment volume (in cubic meters [m^3]) is converted to mass (in metric tons [t]) by multiplying by a factor of 1.517. This conversion factor was obtained by using the methods described in Lara and Pemberton (1963).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

ABS	acoustic backscatter
ADCP	acoustic Doppler current profiler
BCDC	San Francisco Bay Conservation and Development Commission
Delta	Sacramento-San Joaquin Delta
DWR	California Department of Water Resources
EDI	equal-discharge increment
EWI	equal-width increment
MAL	Suisun Bay at Mallard Island, California, streamgage (USGS Station 11185185, DWR Station MAL)
QWEST	Quantifying Waterflow in the Estuary
SFEI	San Francisco Estuary Institute
SSC	suspended-sediment concentration
SJJ	San Joaquin River at Jersey Point streamgage (USGS Station 11337190, DWR Station SJJ)
SRV	Sacramento River at Rio Vista streamgage (USGS Station 11455420, DWR Station, SRV)
USGS	U.S. Geological Survey
WY	water year (begins October 1 of previous year through September 30 of the current year)

Sand Supply to San Francisco Bay from the Sacramento and San Joaquin Rivers of the Central Valley, California

By Mathieu D. Marineau,[1] David Hart,[1] Christopher P. Ely,[1] and Lester McKee[2]

Abstract

Sediment from the Central Valley via the Sacramento-San Joaquin Delta (Delta) and Suisun Bay is a primary source of sand to San Francisco Bay, California. Sand is mined from San Francisco Bay for commercial purposes, such as for use in concrete for construction. To better understand the supply of sand to Suisun Bay and San Francisco Bay, the U.S. Geological Survey (USGS), in cooperation with the San Francisco Bay Estuary Institute (SFEI) and the San Francisco Bay Conservation Development Commission (BCDC), initiated this study to compile and synthesize historical data and estimate the total sediment and sand portion of sediment exiting the Delta to Suisun Bay for a 20-year period between water years 2001 and 2020.

Sediment exiting the Delta is a combination of suspended sediment and bedload sediment. Seaward bedload transport was estimated using bedload transport equations and available hydraulic data at the two downstream-most streamgages in the Delta (where velocity is measured). Those two streamgages are about 25 kilometers upstream from the “exit” of the Delta at Mallard Island. The combined average annual net (seaward) bedload at these two streamgages was estimated to be 0.102 million cubic meters per year (Mm^3/yr) for the study period. This volume of bedload is equivalent to 0.155 million metric tons per year (Mt/yr), assuming a bulk density of 1.517 metric tons per cubic meter (t/m^3). The bedload composition was estimated to be 88 percent sand.

Between the two streamgages and Mallard Island, an annual average of 0.076 Mm^3/yr of material was removed through mining during the study period, of which 97.5 percent was sand. In addition, 0.053 Mm^3/yr was removed through dredging to support shipping and navigation, of which 76 percent was sand. The total volume of mined and dredged sediment material was approximately 0.128 Mm^3/yr, equivalent to 0.194 Mt/yr, assuming a bulk density of 1.517 t/m^3.

Assuming the estimated bedload reaching Mallard Island was reduced by mining and dredging, a mean bedload flux of −0.009 Mm^3/yr was computed (using a bulk density of 1.517 t/m^3), suggesting a deficit or landward transport of bedload. However, the total suspended-sediment and suspended-sand flux was in the seaward direction. The average total suspended flux of sediment to Suisun Bay through the cross section at the Mallard Island streamgage was estimated to be 0.482 million metric tons per year (Mt/yr; 0.015 Mt/yr sand) in the seaward direction. The results indicate a net flux out of the Delta of 0.469 Mt/yr of total sediment and 0.003 Mt/yr of sand.

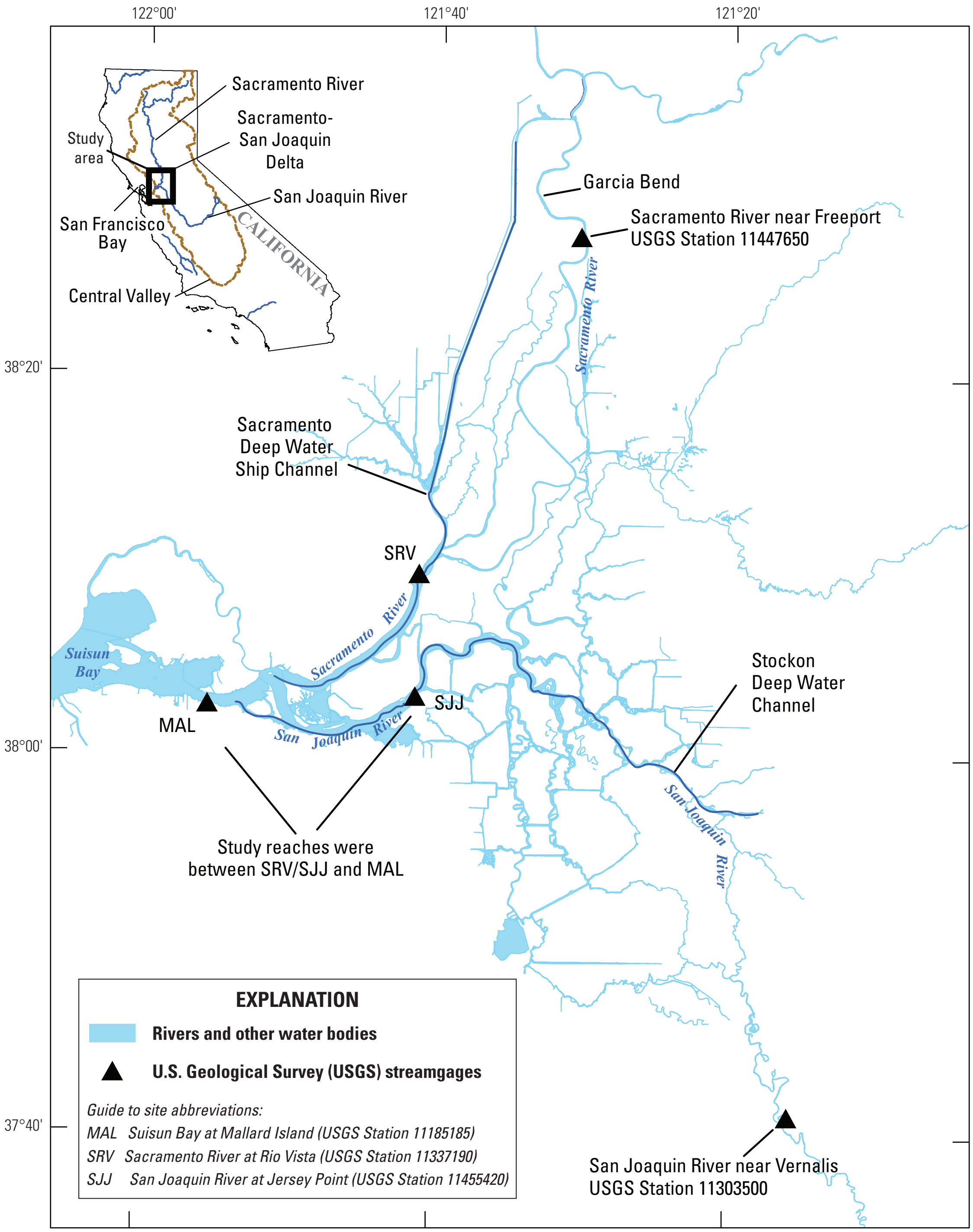
The primary limitation of the study was the lack of physical bedload measurements to validate the bedload estimates. To better refine the estimates of bedload, physical measurements of bedload or repeat bathymetry would be necessary for a range of flow conditions. Such measurements could be used to calibrate transport equations and quantify the uncertainty in such estimates.

Introduction

Sediment from the Central Valley via the Sacramento-San Joaquin Delta (Delta) is a primary source of sand in San Francisco Bay, particularly for sand-mining leases near Mallard Island and in Suisun Bay, California (fig. 1). To better understand the supply of sand to Suisun Bay and San Francisco Bay, the U.S. Geological Survey (USGS), in cooperation with the San Francisco Bay Estuary Institute and the San Francisco Bay Conservation Development Commission (BCDC), initiated this study to compile and synthesize historical data and estimate the total sediment and sand portion of sediment exiting the Delta to Suisun Bay for a 20-year period between water years (WY; the water year is the period from October 1 through September 30 and is named for the calendar year in which it ends) 2001 and 2020. Sand exits the Delta as a combination of suspended-sediment load and bedload measured at a site that is operated cooperatively by the USGS and the California Department of Water Resources (DWR). The streamgage at this site is Suisun Bay at Mallard Island, California (USGS Station 11185185 [U.S. Geological Survey, 2023]), and DWR station MAL (California Department of Water Resources, 2023). The streamgage identifier “MAL” will be used in this report when referring to this streamgage.

[1]U.S. Geological Survey.

[2]San Francisco Estuary Institute Aquatic Science Center.



Base modified from U.S. Geological Survey, Esri, and other Federal and State digital data;
Albers Equal-Area Conic projection, standard parallels 29°30' and 45°30' N.,
central meridian 120° W.; North American Datum of 1983

0 8 16 MILES
0 8 16 KILOMETERS

Figure 1. Map of the Sacramento-San Joaquin Delta, California, showing the monitoring locations used for sand-supply computations in the Central Valley, California.

Directly measuring and computing sediment exiting the Delta is difficult due to the complexity of the channel network and tidal forcing. Previous estimates of sediment exiting the Delta, such as Porterfield (1980), were based primarily on measurements collected upstream from the Delta, including at the Sacramento River at Freeport, California, and the San Joaquin River at Vernalis, California (USGS Stations 11447650 and 11303500, respectively; U.S. Geological Survey [2023]). A later study by Dinehart (2002) estimated bedform transport rates using repeat bathymetry at the Garcia Bend reach in the Sacramento River. Estimates by Porterfield (1980) and Dinehart (2002) were for the upstream areas of the Delta, where most of the sediment is in suspension. In the study by Porterfield (1980), only about 1–2 percent of the sediment entering the Delta was estimated to be transported as bedload. More recent research has indicated that about two-thirds of the total sediment entering the Delta is deposited in the Delta or transitions from suspended-sediment load to bedload (Wright and Schoellhamer, 2005), of which about 20 percent gets removed through dredging (Marineau and Wright, 2014). Because of complex channel dynamics and sediment removal from dredging, the estimates of bedload entering the Delta are not representative of bedload exiting the Delta (Marineau and Wright, 2014).

Purpose

The primary purpose of this study is to provide volumetric estimates of sand exiting the Delta to Suisun Bay from WY 2001 to WY 2020. A secondary purpose is to identify potential sources of error in the estimates of sand load that might be improved with additional data collection or analysis.

The estimates include bedload at the Sacramento River at Rio Vista, California (DWR station SRV; California Department of Water Resources, 2023; USGS Station 11455420), and the San Joaquin River at Jersey Point, California (DWR station SJJ; California Department of Water Resources, 2023; USGS Station 11337190; U.S. Geological Survey, 2023). In this report, the Sacramento River at Rio Vista streamgage is abbreviated as SRV, and the San Joaquin River at Jersey Point streamgage is abbreviated as SJJ (fig. 1). The estimates also include suspended-sediment load at MAL and an adjustment of bedload for sediment removal through dredging and mining between SRV, SJJ, and MAL. These findings can be used to help inform management decisions related to sand supply to San Francisco Bay via Suisun Bay.

Data Collection and Analysis

The following section describes the methods for compiling and analyzing existing suspended-sediment-concentration data, estimating bedload transport exiting the Delta, and compiling relevant dredging and sand-mining data to quantify the effects of those operations on sand-supply estimates.

Sand transported past the MAL streamgage is a combination of both suspended-sediment load and bedload. Bedload is not measured directly at any location in the Delta. In the absence of bedload measurements, bedload transport was estimated at the two nearest upstream USGS streamgages: SRV and SJJ.

Bedload transport at SRV and SJJ was estimated using the van Rijn (1984a, 1984b) equations. The SRV and SJJ sites are upstream from MAL, and there are a mix of dredging and mining activities between Mallard Island and SRV/SJJ streamgages. Bedload reaching Mallard Island was estimated by summing the bedload transport estimates at SRV and SJJ and subtracting the volume of sediment that was removed through dredging and mining activities between SRV/SJJ and MAL. The amount (mass) of sand sediment exiting the Delta is then taken as the combination of bedload (sand fraction) and suspended sand at MAL.

Suspended-Sediment Sampling and Load Computations

Water and sediment from the Central Valley pass through the Delta to Suisun Bay and eventually San Francisco Bay (fig. 1). For this study, Mallard Island was used as the downstream boundary of the Delta (fig. 1). At this location, DWR and USGS have operated the MAL monitoring station from 1994 to present (2024). Turbidity measurements at MAL were used as a surrogate for suspended-sediment concentration (SSC) (Rasmussen and others, 2009). Turbidity measurements were collected at a 15-minute sampling interval at two positions in the water column at the monitoring station (an upper sensor 1 meter [m] below water surface and a lower sensor 1.5 m above bed [for a detailed description, see Buchanan and Morgan, 2014]). In addition, DWR estimated daily (tidally-averaged) streamflow from the Delta to San Francisco Bay at this location using the Dayflow model (California Department of Water Resources, 2019, 2021).

In this study, suspended-sediment load entering San Francisco Bay at Mallard Island was estimated using methods developed by McKee and others (2006). Due to the tidal nature of this location, the method includes both the advective and dispersive load. McKee and others (2006) determined that the upper sensor was most representative of advective load and that the SSC point samples at the MAL streamgage were generally representative of average SSC of the channel cross section.

Between WY 2015 and WY 2020, suspended-sediment samples were collected at the MAL streamgage and analyzed for SSC and particle-size distribution. This dataset included 103 discrete SSC point samples (Haught, 2023), 22 of which had particle-size distribution data. All suspended-sediment data are in the National Water Information System (NWIS; https://waterdata.usgs.gov/nwis; U.S. Geological Survey, 2023). Samples were collected following standard sediment sampling procedures in Edwards and Glysson (1999) and analyzed at a USGS sediment laboratory following the methods described in Guy (1969).

In addition, two acoustic Doppler current profiler (ADCP) cross-section measurements were collected during a high-outflow event (280,000 cubic feet per second; ft^3/s) in the Delta in 2019 (Hart and others, 2021). The ADCP measurements were collected using a boat-mounted RiverPro 600 kilohertz (kHz) ADCP instrument (Teledyne Marine, 2020) and were processed using WinRiver II software (Teledyne RD Instruments, 2001). Acoustic backscatter (ABS) data of the two ADCP measurements were used as a qualitative surrogate for SSC.

The two ADCP measurements were collected on February 26, 2019, approximately 140 m upstream (to the east) from the pier at the MAL streamgage (fig. 2) at the start of flood tide during a period of high outflow from the Delta. The ADCP measurements were collected 86 minutes apart. In addition, two discharge-weighted vertical suspended-sediment samples were collected between the ADCP measurements using a D-96 depth-integrated suspended sediment sampler (Federal Interagency Sedimentation Project, 2001).

The ABS data derived from the ADCP transects were used to qualitatively observe the cross-sectional variability of ABS, which is often used as a surrogate for SSC, and to qualitatively assess if the point measurements of SSC at the pier where the Mallard Island streamgage (MAL) is located would be a suitable proxy for SSC in the cross section. The discrete SSC samples were used to determine the percentage of sand in suspension and if SSC and streamflow were correlated.

Bedload Estimates

At the time of this writing (2024), bedload is not measured at any place in the Delta, and physical bedload samples have not been collected as part of any previous studies in the Delta. Given the absence of bedload measurements, bedload was estimated by applying the van Rijn equations (1984a, equations 1, 2, 17, 18, 22; 1984b, equation 20) at two upstream sites (SRV and SJJ, each about 25 kilometers (km) upstream from Mallard Island; fig. 1). The bedload transport formulae developed by van Rijn (1984a, 1984b) were chosen because of their ability to incorporate changes in hydraulic roughness due to bedforms and the performance of predicted values against large sets of available bedload data. These two sites were used because of the long-term availability of stage, streamflow, and velocity records, which are required for most bedload transport equations. The streamgage at MAL does not have streamflow or velocity records. One limitation of using the van Rijn equations to estimate bedload is that they assume transport-limited conditions.

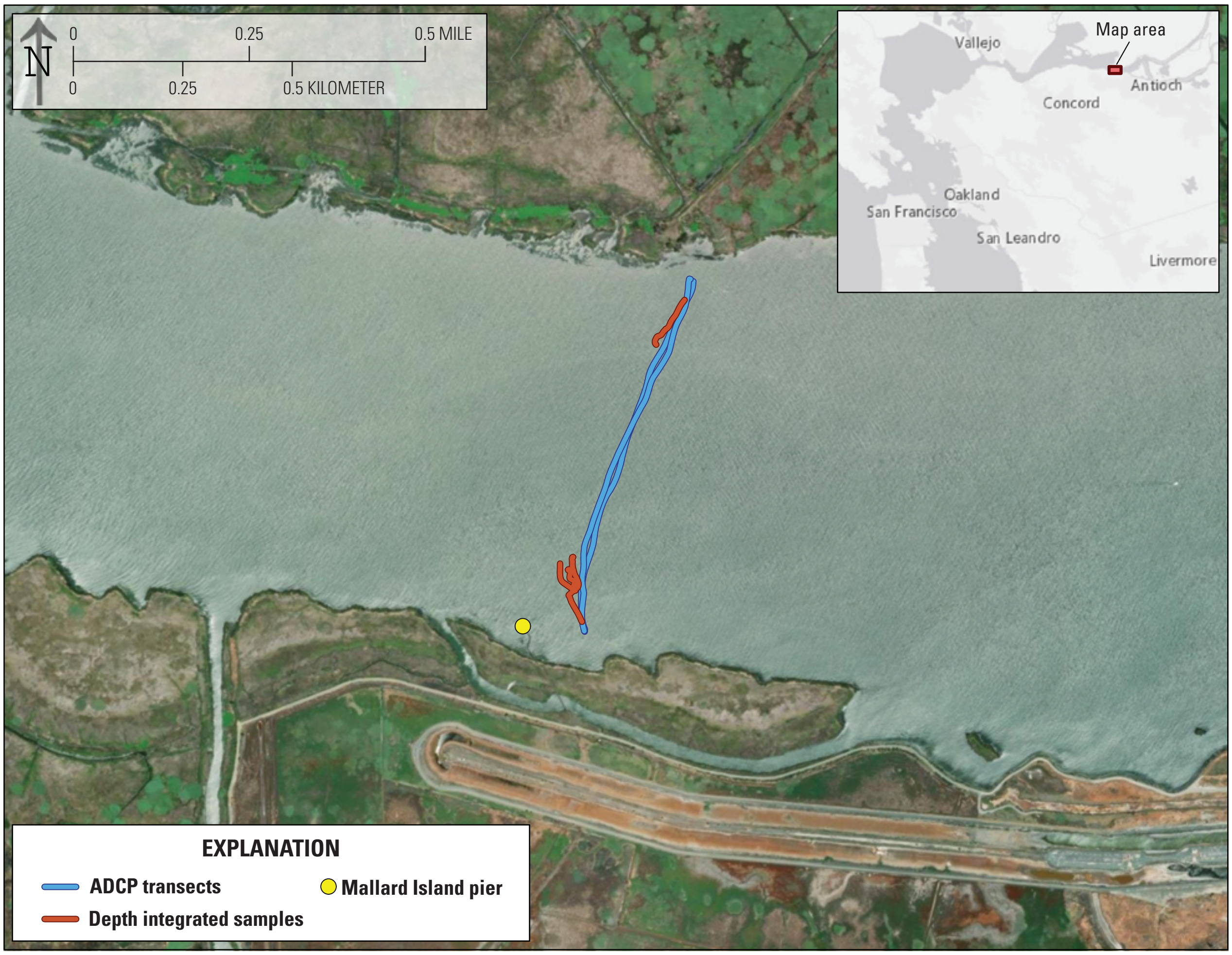
The input requirements for the van Rijn (1984a, 1984b) equations include time series of stage, cross-sectional area, and mean channel velocity, and discrete values of 50th percentile (median) particle size diameter (D_{50}), 90th percentile particle size (D_{90}), and bedform (dunes) dimensions (average length and height).

Stage and velocity at SRV and SJJ were recorded at 15-minute intervals at the USGS streamgages, and data were accessed from NWIS (U.S. Geological Survey, 2023). Cross-sectional area time series were computed using stage and measurements of channel cross sections and were made available by Ely and Marineau (2023).

Bed-material particle size was determined from samples previously collected between 2010 and 2013 and published in Marineau and Wright (2017). Average bedform dimensions were measured in 2012 from several 100–130-m longitudinal depth profiles. Bedform dimensions are used to estimate surface roughness in the van Rijn equations (van Rijn, 1984b).

The sand portions of the bedload (the material in transport) at SRV and SJJ were assumed to be the same as the sand portion of the bed-material sediment samples collected at those sites. The sand portion was averaged from all bed-material samples collected at each respective site between 2010 and 2013 (Marineau and Wright, 2017).

Bed-material particle sizes at each site did not change substantially from year to year, and channel cross-sectional area generally did not change in the Delta. However, bedforms were only measured one time, and their dimensions were assumed static for the period of study (WY 2001–20).



Base map from Esri and its licensors, copyright 2022; Albers Equal-Area Conic projection, standard parallels 29°30′ and 45°30′ N., central meridian 120° W.; North American Datum of 1983

Figure 2. Map of the pier at the Mallard Island at Suisun Bay, California, streamgage (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL) and the February 2019 acoustic Doppler current profiler (ADCP) transects. Two ADCP transects (blue), and two depth-integrated vertical samples (red) were collected on the northern and southern extents (defined by thalweg) to investigate variability in suspended-sediment concentration distribution across the channel cross section. Depth-integrated samples consisted of one vertical sample collected using a D-96 sediment sampler.

However, bedforms in fluvial environments can often change with increasing or decreasing streamflow (Julien and Klaassen, 1995; Dinehart, 2002). In the Dinehart (2002) study in the Sacramento River, bedforms washed out during high flow conditions and transitioned to a plane-bed condition. A plane-bed condition occurs when stream velocity is high enough to wash out bedforms, resulting in a smooth bed without bedform roughness. Particle-size and bedform dimensions are used to calculate hydraulic roughness (van Rijn, 1984b), which can have a large effect on the bedload transport estimates. For this study, two estimates are made: a low and high estimate. The low estimate assumes plane-bed conditions and only uses particle size to compute a hydraulic roughness (van Rijn, 1984a), which is used for all time steps in the bedload estimate calculations. The high estimate uses particle size and bedform dimension to compute hydraulic roughness (van Rijn, 1984b).

As discussed in the “Introduction” section, the Delta traps about two-thirds of the sediment inflow, and much of the bedload and sand is likely mined and dredged (Marineau and Wright, 2014). Therefore, mined and dredged sand-size material was removed from upstream estimates of bedload to produce a total estimate of sand being transported out of the Delta through the Mallard Island cross section.

Sediment Density Estimates and Particle Size Classification

Estimates of bedload in this report were computed in volume of sediment. Bedload volumes were then converted to mass using the Lara and Pemberton (1963) empirical equation (eq. 1) for type IV (riverbed sediments):

$$\gamma = W_c\rho_c + W_m\rho_m + W_s\rho_s \qquad (1)$$

where

- γ is bulk density,
- W is a coefficient from table 3 of Lara and Pemberton (1963), which depends on the type of reservoir operation,
- ρ is a percentage,
- c is clay,
- m is silt, and
- s is sand.

Descriptions of sediment classes (clay, silt, sand, gravel) in this report are based on the Wentworth (1922) scale. Clay was defined as sediment particles smaller than 0.004 millimeters (mm), silt was greater than or equal to 0.004 mm but smaller than 0.0625 mm, sand was greater than or equal to 0.0625 mm but smaller than 2 mm, and gravel was larger than 2 mm. The terms “fine sediment” or “fines” refer to the combination of clay and silt sizes and include all particles less than 0.0625 mm.

The values for the coefficients W_c, W_m, and W_s, assuming a type IV reservoir operation (riverbed sediment; Lara and Pemberton [1963]), are 60, 73, and 97, respectively, which provide a bulk density result in English units of pounds per cubic foot (lb/ft^3). The percentages of clay, silt, and sand (including coarse sand and gravel) were determined by averaging bed-material samples for each site collected between 2010 and 2013 (Marineau and Wright, 2017). At SJJ, the composition measured was 3-percent clay, 11-percent silt, and 86-percent sand (which included 8-percent gravel). At SRV, the composition measured was 1-percent clay, 2-percent silt, and 97-percent sand (less than one-half of a percent of the material was larger than 2 mm). The average for the two sites is 2-percent clay, 6.5-percent silt, and 91.5-percent sand (which includes 4-percent gravel).

Using the percentages of clay, silt, and sand in the equation above results in a bulk density estimate of 94.7 lb/ft^3, which is equivalent to 1.517 metric tons per cubic meter (t/m^3). This bulk density estimate was used in this report to convert volumetric bedload transport estimates to mass.

Compilation and Analysis of Dredging and Sand-Mining Data

The objective of this study was to determine the annual volume and mass of sediment (and sand portion of that sediment) that exits the Delta at MAL (fig. 1). Bedload transport was estimated at the next two upstream streamgages (SJJ and SRV; fig. 1), which are about 25–28 km upstream from MAL. In the study reach between these streamgages, sediment is removed by dredging and sand-mining operations. The estimate of bedload transport reaching MAL from SJJ and SRV is adjusted by subtracting the amount of dredged and mined sediment in that section between MAL and the upstream streamgages (SJJ and SRV).

Annual sediment dredging quantities for the Sacramento River Deep Water Ship Channel and the Stockton Deep Water Channel were provided by the U.S. Army Corps of Engineers; dredged sediment particle-size data were also provided by the U.S. Army Corps of Engineers and were used to estimate the sand portion of the dredged material (Charity Meakes and Nancy Lam, U.S. Army Corps of Engineers, Sacramento Branch, written commun., 2022).

Annual sand-mining volumes for the Suisun Associates 7781 lease area (most of which is upstream from the MAL streamgage cross section) were obtained from Brenda Goeden (BCDC, written commun., 2022) for the WY 2001–20 period. Particle-size information for a subset of those years (2017–20) was provided by Lind Marine (Bill Butler, Vice President of Programs and Compliance at Lind Marine, written commun., 2021).

Results

The following section provides estimates of suspended sediment at the MAL streamgage, annual volume of dredged and mined sediment between SRV, SJJ, and MAL, bedload estimates at SRV and SJJ, and lastly, estimates of the total annual sand-sized sediment transport at the MAL streamgage.

Suspended-Sediment Supply

Results are presented regarding suspended-sediment variation in the MAL streamgage cross section. Then, variation in the percent sand in suspension at this cross section relative to streamflow is shown. Finally, total suspended-sediment load and suspended-sand load results are presented.

Suspended-Sediment Variation in the MAL Streamgage Cross Section

Results from the two discharge-weighted vertical samples indicated higher SSC in the northern section of the cross section (63 milligrams per liter [mg/L]) and lower concentration in the southern section (45 mg/L; red lines shown in fig. 2), which align with the ADCP backscatter data that also indicate more backscatter in the northern section of the channel (fig. 3). Because a new ABS-SSC model (Landers and others, 2016) cannot be developed with only two samples, the two discharge-weighted vertical samples were tested against an ABS-SSC model developed in the Delta, which has similar suspended-sediment size distribution (Work and others, 2021). The SSCs from the two samples were outside the confidence interval of the model; therefore, the model was not used to convert ABS from the transects to SSC.

The results from transects demonstrated that SSC varied spatially throughout the cross section. These transects were collected during high outflow from the Delta (280,000 ft^3/s), and this trend in spatial variability at high flows (>200,000 ft^3/s) has been observed previously at the site (fig. 4). During low and moderate flows (4,000 and 64,000 ft^3/s), which comprised 91 percent of average daily flow conditions (California Department of Water Resources, 2019, 2021), the cross section was well mixed, and SSC data collected from the MAL pier (derived from surrogate turbidity) were representative of the cross-sectionally averaged SSC from previous equal-discharge-increment (EDI) transects. We assumed that estimates of SSC based on the upper turbidity sensor at the MAL streamgage pier (following the methods of McKee and others [2006]) are representative of the water column during all flow conditions when we estimated the downstream mass flux of total suspended sediment at the MAL streamgage for WY 2001–21 (app. 1, table 1.2).

Variation in Percentage of Sand in Suspension in Relation to Flow Conditions

The percentage of sand in suspension was investigated for samples collected at the MAL streamgage. Samples analyzed include EDI samples (Edwards and Glysson, 1999), the new vertical discharge-weighted samples from 2019, and SSC point samples collected using a horizontal, Van Dorn-type sampler (Ward and Harr, 1990) at the pier with the MAL streamgage (fig. 5). Only SSC was routinely sampled at MAL, so the number of samples analyzed for sand percentage is small. EDI samples were separated into each vertical subsample to account for lateral variability. Sand percentage from the dataset ranged from 0 to 21.9 percent and yielded a mean sand percentage of 2.8±0.3 percent (standard error of the mean), which was rounded to 3 percent for this study.

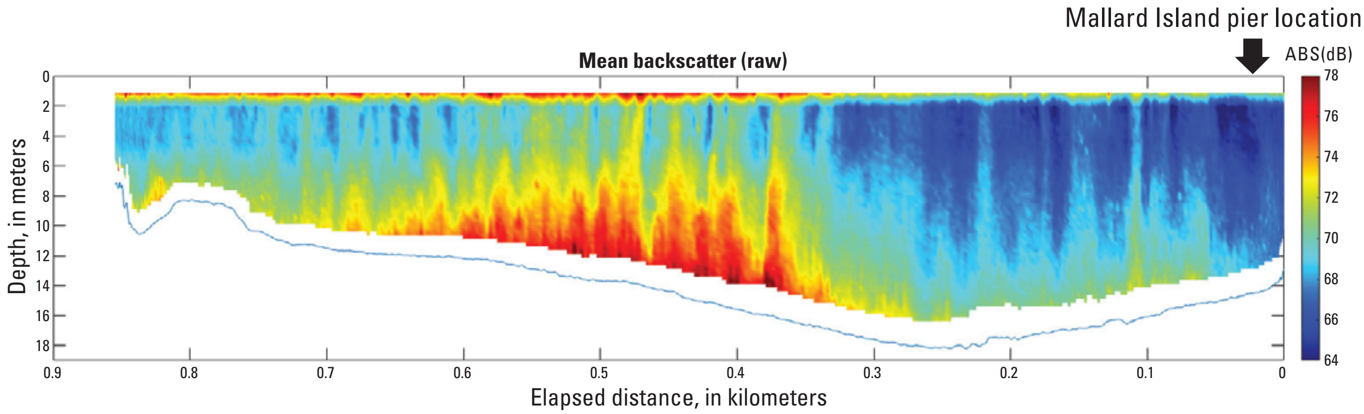
Correlation was checked between percentage of sand and streamflow exiting the Delta (fig. 6). Discharge was calculated using a modified, non-tidally filtered QWEST (calculated streamflow moving west from the Delta; QWEST stands for Quantifying Waterflow in the Estuary), which combined streamflows from four streamgages in the Delta (Ganju and Schoellhamer, 2006). The correlation yielded a poor fit with a coefficient of determination (R^2) of 0.0669, indicating that streamflow was a poor predictor of sand percentage.

The effect of tidal patterns on the sand percentage was also explored. Tidal-stage data from the MAL streamgage were downloaded from the California Data Exchange Center (California Department of Water Resources, 2023). Tidal-stage data were only available on an hourly basis; therefore, the time of sand percentage sampling was rounded down to the beginning of the hour and averaged if more than one sample was collected within the hour. The time was rounded down to the beginning of each hour because there is usually a lag in tidal energy (slack water usually happens 1–2 hours after the lowest tide stage). Individual vertical samples from EDI measurements were used instead of average EDI values because samples often took more than an hour to collect at this site. The data were then graphically analyzed to check for a correlation between sand percentage and tide stage using 0-, 1-, and 2-hour lags. No correlation was detected.

In summary, neither QWEST (calculated streamflow moving west from the Delta) nor tidal stage could be used as surrogates to estimate sand percentage. From the observations, 3 percent of total suspended sediment that passes through the MAL streamgage cross section is sand sized and is used in the calculations (app. 1, table 1.1).

Total Suspended-Sediment Load and Suspended-Sand Load

Based on the methods of calculating suspended-sediment flux and suspended-sand fraction discussed above, the mean annual suspended-sediment load was 0.482 million metric tons (Mt) for the WY 2001–20 period and ranged from 0.096 to 2.17 Mt (app. 1, table 1.1). This mean annual suspended-sediment load is less than the 0.73 Mt reported more recently by Schoellhamer and others (2018). In the case of suspended sand, the mean annual load was 0.014 Mt for the 20-year period and ranged from 0.003 Mt (WY 2014) to 0.065 Mt (WY 2017). These estimates will be discussed in relation to climate in a later section of the report called “Suspended-Sediment Flux and Annual Climate Variability.”



ABS(dB), acoustic backscatter in units of decibels.

Figure 3. Plot of mean acoustic backscatter (ABS) from one of the acoustic Doppler current profiler (ADCP) cross-section measurements collected in February 2019 in the channel adjacent to the Suisun Bay at Mallard Island, California, streamgage (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL). The black arrow indicates the general location of the pier with the MAL streamgage. Note the high ABS values in the northern (leftmost) part of the channel relative to the pier.

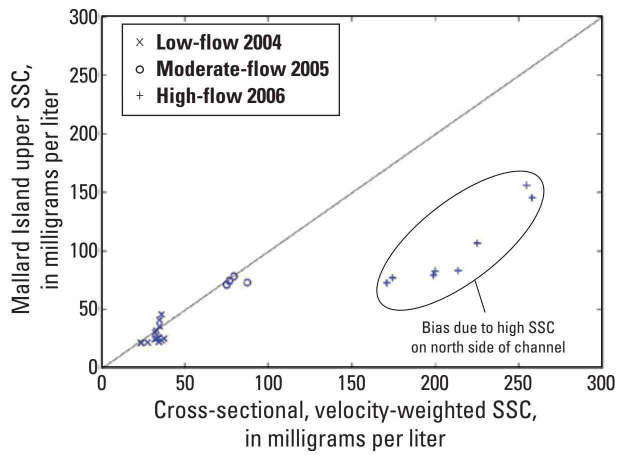


Figure 4. Graph showing equal-discharge-increment samples (x-axis) collected during three flow conditions compared to point samples collected at the Suisun Bay at Mallard Island, California, streamgage (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL) pier (y-axis). Low, moderate, and high flows are 4,000, 64,000, and 340,000 cubic feet per second, respectively. The pier is on the southern side of the channel. During high flows, samples from the pier are lower than the cross-sectional average due to high suspended-sediment concentrations (SSC) on the northern side of the channel.

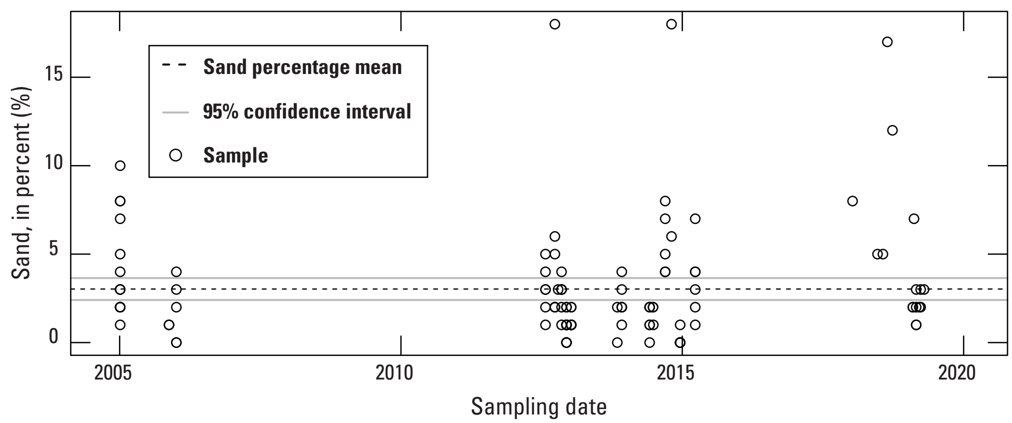


Figure 5. Graph showing percentage of sand from all publicly available suspended-sediment concentration samples collected during water years 2005 to 2020. Samples include point samples, single vertical samples, and equal-discharge-increment samples from along the cross section at the Suisun Bay at Mallard Island, California, streamgage (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL).

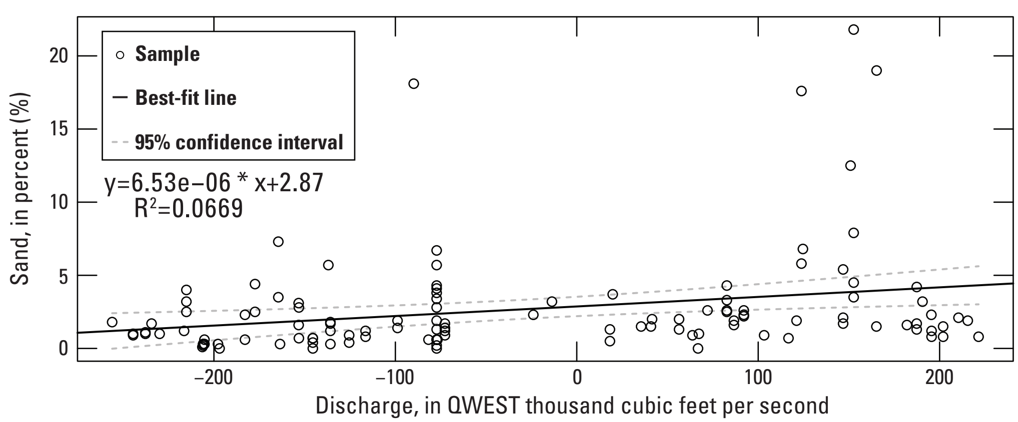


Figure 6. Graph showing sand percentage from all publicly available suspended-sediment concentration samples collected from water years 2005–20 at the Suisun Bay at Mallard Island streamgage (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL) compared to streamflow discharge exiting the Delta (following methods described by Ganju and Schoellhamer [2006]). The correlation yielded a poor fit (R^2=0.0669).

Bedload Transport Estimates

Seaward bedload transport was estimated at the two upstream streamgages (SRV and SJJ) for the WY 2011–20 period. Annual results for the WY 2001–10 period were published previously (Schoellhamer and others, 2018) and are also provided (app. 1, table 1.1). For the WY 2011–20 period, two estimates were made (a "low" estimate and a "high" estimate), as described in the "Data Collection and Analysis" section of this report. The estimates were calculated using a 15-minute time step and then averaged over the water year to determine the net (seaward) transport. The average annual volume of bedload moving seaward at the upstream streamgages (SRV and SJJ) for the WY 2011–20 study period was estimated to be between 0.038 million cubic meters per year (Mm^3/yr; low estimate) and 0.202 Mm^3/yr (high estimate). The high and low estimates represent an average of 0.182 Mm^3/yr with a standard deviation of 0.125 Mm^3/yr. The annual results are provided in table 1.1 of appendix 1. Low and high estimates were not calculated for WY 2001–10 because of limited source data. For the entire study period (WY 2001–20), the average annual volume of bedload moving seaward at streamgages SRV and SJJ was 0.128 Mm^3/yr. Full time series of bedload estimates at SRV and SJJ for the WY 2011–20 period are available from Ely and Marineau (2023). Using a dry bulk density conversion factor of 1.517 t/m^3 (see "Data Collection and Analysis" section for details on the conversion assumptions), the mean annual mass of bedload for the WY 2010–20 study period was 0.057 million metric tons per year (Mt/yr; low estimate) to 0.307 Mt/yr (high estimate), or 0.128 Mt/yr for the entire study period (WY 2001–20). Figure 7 shows annual estimates of bedload for SRV, SJJ, and combined (SRV+SJJ) for the study period.

Total bedload estimates varied from year to year, but the greatest estimated bedload transport rates happened in WY 2017. Water year 2017 had major storm events with substantial outflow from the Central Valley. The total seaward bedload for WY 2017 (at SJJ+SRV) was estimated to be 0.689 Mm^3/yr (1.039 Mt/yr, assuming a conversion rate of 1.517 t/m^3). The average annual bedload rate for all other years was estimated at 0.113 Mm^3/yr. The estimated WY 2017 bedload at SRV and SJJ was about 6 times the average annual rate for the other years in the WY 2001–20 study period. On average, during the WY 2001–20 period, the sand portion of bedload that was transported seaward at SRV and SJJ was estimated to be about 88 percent of the total bedload, or about 0.067 ± 0.099 Mm^3/yr, which is equivalent to 0.151 Mt/yr (assuming a bulk density of 1.517 t/m^3).

Dredged and Mined Sediment

The SRV and SJJ streamgages 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 MAL streamgage (fig. 1). In the 25 km between SRV/SJJ and MAL, bedload transport volumes were reduced by sand-mining operations and maintenance dredging for ship navigation.

During the WY 2001–20 study period, a total of 1.050 Mm^3 of sediment was removed through dredging operations to support shipping and navigation in the reaches between MAL and SRV/SJJ. The average annual volume removed was 0.053 Mm^3/yr, of which approximately 76 percent (0.040 Mm^3) was sand. The total annual volume of sediment mined on the Sacramento River upstream from MAL during WY 2001–20 was approximately 1.518 Mm^3, or an average annual volume of 0.076 Mm^3/yr. Figure 8 shows a time series of annual quantities of sediment removed through mining or dredging operations.

Particle-size analysis data were only available for WY 2017–20 and indicated that the sediment mined was predominantly sand: 97 percent of the sediment was between 0.07 mm and 2.4 mm, which generally corresponds to sand sizes on the Wentworth classification scale (Wentworth, 1922). About 0.9 percent was larger than 2.4 mm (fine gravels), and 1.6 percent was smaller than 0.07 mm (silts and clay). There was no discernible trend in particle size within years over the 4-year period; therefore, we assumed that the particle-size distribution for the WY 2017–20 period was representative of the past 20 years and that the sand portion of the mined sediment was approximately 97 percent of the total sediment.

Total Sand Load at the MAL Streamgage

The total estimated volume of material removed through dredging and mining (between MAL and SRV/SJJ) during the 20-year study period exceeded the estimated seaward bedload fluxes. During that period, 2.211 Mm^3 of material was removed, and seaward bedload was estimated to be 2.033 Mm^3. The volume of material removed through dredging exceeds the seaward estimate of bedload, which results in a deficit of bedload entering Suisun Bay at Mallard Island of 0.009 Mm^3/yr (or 0.013 Mt/yr, assuming a conversion rate of 1.517 t/m^3). This deficit might be interpreted as a landward flux; however, we assume the uncertainty in these estimates is large even though we could not quantify the uncertainty (app. 1, table 1.2).

Total suspended sediment was in the seaward direction and was larger in magnitude than the (landward) deficit of bedload. Therefore, the net sediment flux from the Delta to Suisun Bay through the MAL streamgage cross section was estimated to be 0.47 Mt/yr in the seaward direction (app. 1, table 1.2). On average, the results indicated a net flux of sand out of the Delta (at MAL) of 0.003 Mt/yr (app. 1, table 1.2).

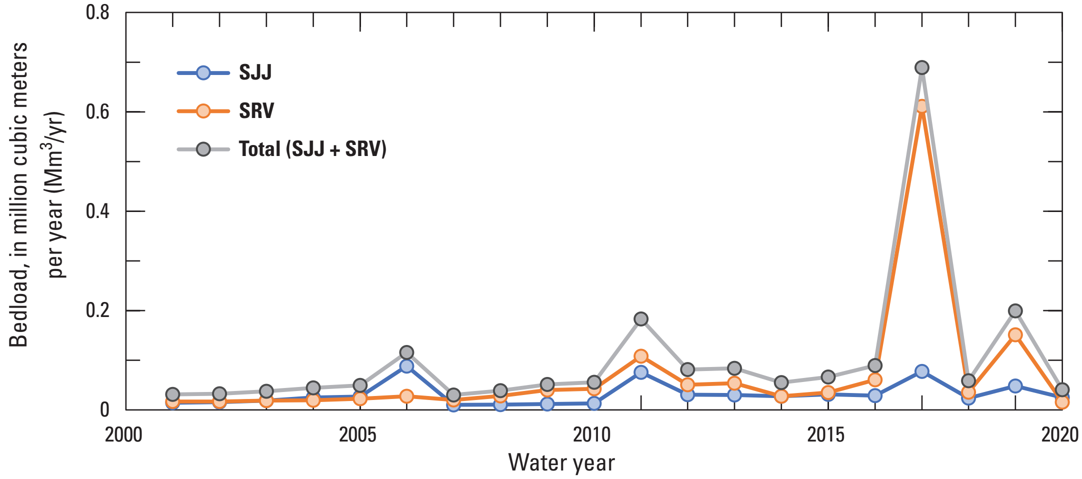


Figure 7. Graph showing annual volumetric seaward bedload estimates at the Sacramento River at Rio Vista, California, streamgage (U.S. Geological Survey [USGS] Station 11455420, California Department of Water Resources [DWR] Station SRV), the San Joaquin River at Jersey Point, California, streamgage (USGS Station 11337190, DWR Station SJJ), and their combined total (SRV+SJJ) for water years 2001–20.

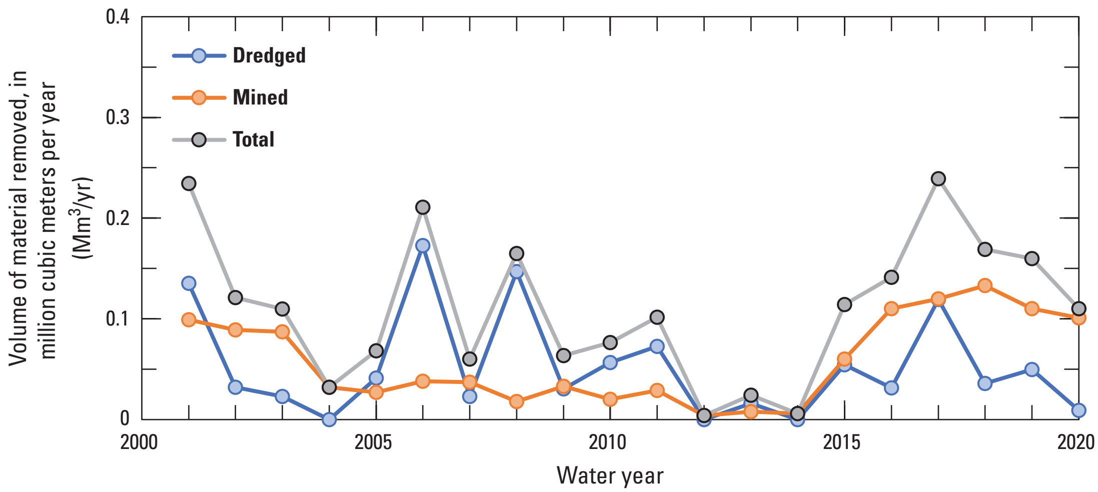


Figure 8. Graph showing annual volumes of mined and dredged material (water years 2001–20) between the Suisun Bay at Mallard Island, California, streamgage (U.S. Geological Survey [USGS] Station 11185185, California Department of Water Resources [DWR] Station MAL) and the Sacramento River at Rio Vista, California, streamgage (USGS Station 11455420, DWR Station SRV) and the San Joaquin River at Jersey Point, California, streamgage (USGS Station 11337190, DWR Station SJJ).

Discussion

The following section discusses sources of potential error, annual climatic variability in suspended-sediment flux, and improvements to reduce uncertainty in future estimates of suspended-sediment load and bedload.

Sources of Potential Error

Suspended-sediment particle-size data were not sufficient to derive a tidally or streamflow-dependent dynamic suspended-sediment load model but did expose areas of SSC variation unaccounted for in the regression model (shown in fig. 6). McKee and others (2006) analyzed error of computed suspended-sediment load at MAL using the upper sensor of the MAL streamgage to calculate sediment flux, which resulted in an error of ±32 percent that accounted for total errors in tidal variation, Dayflow data, laboratory analysis, turbidity-SSC regression models, and vertical and cross-sectional variabilities. More recent data (Hart and others, 2021) indicate that the previous estimate of cross-sectional variability in suspended sediment was underestimated at higher discharge values. Data collected during the high-outflow event (280,000 ft^3/s) from the Delta indicated cross-sectionally average SSC varying from 28 to 50 percent of SSC from the MAL pier based on discharge-weighted vertical samples and ABS. SSC samples, including sand percentage taken after the McKee and others (2006) study, indicated a root mean squared error of 1.8 percent in the 3 percent sand fraction model assumption. Accounting for the cross-sectional variation measured in the 2019 high-outflow event, the total computed error for sand fraction calculations increases from ±32 to ±52 percent, with the predominant source of error being cross-sectional heterogeneity.

Bedload was not measured at any point during the study period at any of the study sites. Estimates of bedload were calculated using sediment particle-size data from bed-material samples, which were collected only a few times during the study period, and bedform dimension data were collected only once. Bedform dimensions and types are known to change with different flow conditions and sediment supply (Julien and Klaassen, 1995; Dinehart, 2002). Bedload estimates may include uncertainty caused by assuming static bedform dimensions and particle sizes as inputs in the bedload transport formulae, particularly with regard to changing bedform conditions. Bedforms have “washed out” during high flows, in which the bed transitions from well-formed dunes to a plane bed (Dinehart, 2002). In this study, four different time series were computed. For each of the two sites (SRV and SJJ), one time series was produced assuming plane-bed conditions for the entire study period, and one time series was produced by applying the 2012 measured bedform dimensions to the entire study period.

Another primary source of error in the bedload estimates is due to relying solely on the van Rijn (1984a, 1984b) transport equations in the absence of physical bedload measurements that could be used to validate the estimates. In comparison to a compilation of published bedload datasets, the estimates produced from the van Rijn equations ranged from 0.33 to 3 times the measured (published) bedload values approximately 93 percent of the time (van Rijn, 1984a).

Suspended-Sediment Flux and Annual Climate Variability

The flux of total suspended sediment was closely related to Delta outflow (fig. 9). Water year 2017 delivered 23 percent of the 20-year total suspended sediment. Overall, just 4 water years delivered 52 percent of the 20-year total suspended-sediment load to Suisun Bay. These results illustrate the importance of wet years for sediment transport and the importance of collecting data during a variety of conditions, including wet years. A comparison of bedload estimates with streamflow was not made because the equations use streamflow as one of the main input variables, and bedload was not measured.

The mean total suspended-sediment flux of 0.482 Mt reported here is less than previously reported values: 1.2 Mt (McKee and others, 2006), 0.89 Mt (McKee and others, 2013), and 0.73 Mt (Schoellhamer and others, 2018). Observed differences likely result from two factors: average streamflow during this study period was lower than previous studies, and an overall shift in SSC was observed starting in 1999, which was just before this study period began.

Streamflow during WY 2001–20 (the period of this study) averaged just 17.9×10^9 m^3/yr, which is drier than the recent 30-year mean (21.0×10^9 m^3/yr) and drier than the mean annual flow conditions discussed in the previous studies: 28.4×10^9 m^3/yr (WY 1995–04; McKee and others, 2006), 24.5×10^9 m^3/yr (WY 1995–10; McKee and others, 2013), and 21.5×10^9 m^3/yr (WY 1995–16; Schoellhamer and others, 2018). Because flow is strongly correlated with suspended-sediment mass flux (fig. 9), the climatic period during which the data are averaged has a large effect on mean suspended-sediment loads.

The data averaging period was entirely after 1999, the year that a statistically significant step decrease of 36-percent SSC was observed in San Francisco Bay based on a comparison of data from WY 1991–98 and WY 1999–07 (Schoellhamer, 2011). Schoellhamer (2011) presented a hypothesis that this phenomenon results from crossing a threshold from transport-limited conditions to supply-limited conditions because the erodible sediment pool from the gold mining era of the 19th century was finally depleted. Schoellhamer and others (2018) further explored this hypothesis using double mass plots and indicated that the data supported the hypothesis for an extended period through 2016. The wetter years of WY 2006 (51.3×10^9 m^3/yr) and WY 2011 (33.2×10^9 m^3/yr) did not indicate elevated SSC or any deviation from the 1999–2016 regression slope (Schoellhamer and others, 2018). The mean slope was 45.5 mg/L for 1995–98 and 25.2 mg/L for 1999–2016. Repeating this same analysis to include the data in this study (through WY 2020), the mean slope for 1999–2020 is 26.3 mg/L (fig. 10).

Improvements to Reduce Uncertainty

Additional measurements of bedload and suspended sediment (primarily cross-sectional sampling) in strategic locations could improve the accuracy of estimates of sand load exiting the Central Valley at the Delta. Analyzing samples for fine/sand split would facilitate the determination of the sand percentage in the sediment load.

Physical measurements of bedload were not collected at the sites used in this study during the study period (WY 2001–20). Cross-sectional measurements in the form of EDIs and equal-width increments (EWIs; Edwards and Glysson, 1999) of suspended sediment were collected periodically, but additional EDI/EWI measurements at a range of flow conditions would be needed to determine if point measurements at the MAL streamgage are representative of the channel cross section or if an adjustment coefficient is warranted (Edwards and Glysson, 1999; U.S. Geological Survey, 2006; U.S. Geological Survey, 2016).

Two improvements that could help increase the accuracy of suspended-sand flux estimates at MAL include improvements in understanding (1) the cross-sectional heterogeneity of suspended-sediment flux and (2) sand fraction with discharge. As noted previously, variability of SSC in the channel cross section may account for ±32 to ±52 percent of the uncertainties in current estimates. Also, streamflow velocity was not measured on site. Continuous streamflow velocity measurements at the MAL streamgage could reduce the variations observed.

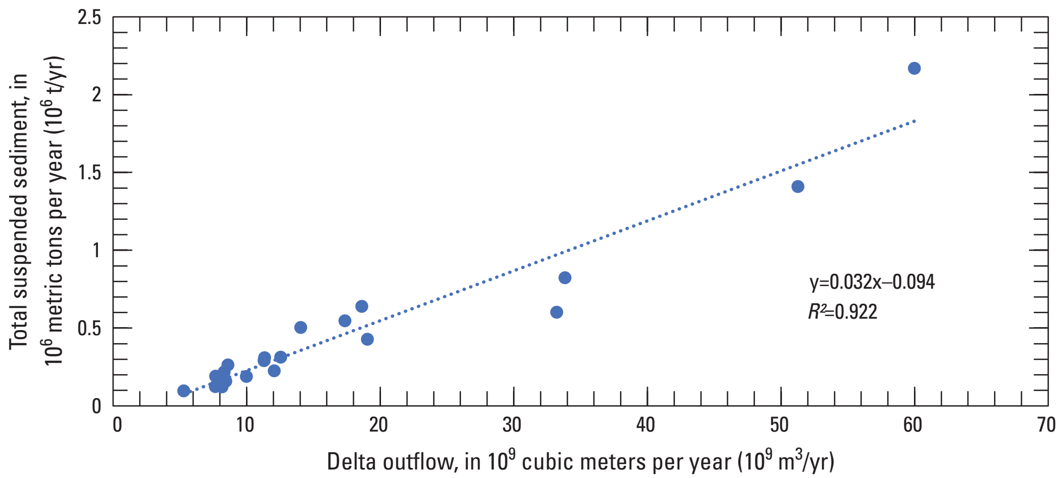


Figure 9. Graph showing correlation between Delta outflow and total suspended-sediment load for Suisun Bay at the Mallard Island, California, streamgage (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL).

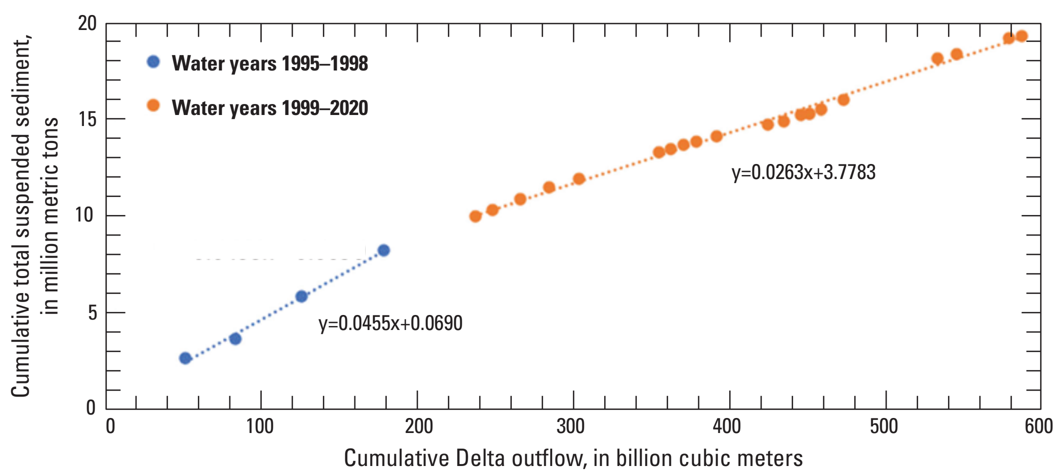


Figure 10. Graph showing a double-mass diagram for suspended-sediment flux at the Suisun Bay at Mallard Island, California, streamgage (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL). The blue line for the 1995–98 data has a slope of 0.0455 million metric tons (Mt) per 10^9 cubic meters, which is equivalent to 45.5 mg/L (Schoellhamer, 2011), and the orange line for the 1999–2020 data has a slope of 0.0263 million metric tons (Mt)t per 10^9 cubic meters, equivalent to 26.3 mg/L, consistent with a step decrease in water year 1999.

Suspended-Sediment Loads

Cross-sectionally averaged SSC measurements (either EWIs or EDIs) would be needed to develop a relation between point SSC measurements at the MAL streamgage and the rest of the cross section. To estimate the sand portion of suspended sediment, the suspended-sediment samples could be analyzed for SSC and sand/fine split. Collecting SSC measurements throughout a range of streamflow conditions and seasons could help to develop a robust relation between turbidity at the MAL streamgage and cross-sectionally averaged SSC and sand percentage.

Bedload Measurements

For this study, bedload transport was estimated using transport formulae (van Rijn, 1984a, 1984b) and limited field data. In a comparison of similar estimates to published field data in other rivers, the estimates were within 0.33 to 3 times the actual bedload approximately 94 percent of the time (van Rijn, 1984a). Physical measurements of bedload were not available to compare with the estimates and quantify the certainty of the estimates provided in this study. In addition, estimates made for two upstream locations in the Delta were adjusted based on mining and dredging removals. A more accurate estimate of bedload exiting the Delta at MAL could involve making bedload transport estimates and measurements at the MAL streamgage location. However, a streamflow rating curve would also need to be developed at the MAL streamgage to help quantify bedload.

Bedload measurements are needed to validate bedload transport estimates made using sediment transport equations. The recommendation by Edwards and Glysson (1999) is to collect bedload measurements throughout a range of flow conditions to develop a robust relation between streamflow and bedload transport. Measurements would ideally be collected annually for validation similar to published USGS guidance for suspended-sediment models (U.S. Geological Survey, 2016).

Additional bed-material sediment samples would help determine if particle-size distribution changes through time. Physical samples of bedload transport may be logistically impractical; however, repeat bedform mapping during a variety of flood flow conditions may be used to ground truth the estimates of bedload at SRV and SJJ.

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Appendix 1.

Table 1.1. Estimated annual bedload sediment transport at the Sacramento River at Rio Vista, California, streamgage (U.S. Geological Survey [USGS] Station 11455420, California Department of Water Resources [DWR] Station SRV), San Joaquin River at Jersey Point, California, streamgage (USGS Station 11337190, DWR Station SJJ), and sediment removed through mining and dredging operations in the reaches upstream from Suisun Bay at Mallard Island, California, streamgage (USGS Station 11185185, DWR Station MAL) to SRV and SJJ.

[Mm^3/yr, million cubic meters per year; —, not applicable]

Water year	Estimated total bedload at SRV and SJJ[1] (Mm^3/yr)	Estimated bedload (low-range[2]) at SRV and SJJ (Mm^3/yr)	Estimated bedload (high-range[3]) at SRV and SJJ (Mm^3/yr)	Estimated bedload, annual average at SRV and SJJ (Mm^3/yr)	Total sediment mined upstream from MAL (Mm^3/yr)	Total sediment dredged upstream from MAL (Mm^3/yr)	Estimated net total bedload at MAL[4,5] (Mm^3/yr)
2001	0.031	—	—	0.031	0.099	0.135	−0.203
2002	0.032	—	—	0.032	0.089	0.032	−0.089
2003	0.038	—	—	0.038	0.087	0.023	−0.072
2004	0.044	—	—	0.044	0.032	0	0.012
2005	0.049	—	—	0.049	0.027	0.041	−0.019
2006	0.115	—	—	0.115	0.038	0.173	−0.096
2007	0.030	—	—	0.030	0.037	0.023	−0.030
2008	0.039	—	—	0.039	0.018	0.147	−0.126
2009	0.051	—	—	0.051	0.033	0.031	−0.013
2010	0.056	—	—	0.056	0.020	0.057	−0.021
2011	—	0.043	0.324	0.184	0.029	0.073	0.082
2012	—	0.016	0.147	0.082	0.004	0	0.078
2013	—	0.017	0.150	0.084	0.008	0.016	0.060
2014	—	0.011	0.098	0.055	0.006	0	0.049
2015	—	0.013	0.119	0.066	0.060	0.054	−0.048
2016	—	0.018	0.160	0.089	0.110	0.031	−0.052
2017	—	0.186	1.192	0.689	0.120	0.119	0.45
2018	—	0.012	0.106	0.059	0.133	0.036	−0.110
2019	—	0.051	0.348	0.200	0.110	0.050	0.040
2020	—	0.008	0.073	0.041	0.101	0.009	−0.069
Total	0.485	0.375	2.717	2.034	1.161	1.050	−0.177
Mean	0.049	0.038	0.272	0.102	0.058	0.053	−0.009

[1]Source of total estimated bedload for water years 2001–10: Schoellhamer and others (2018).

[2]Low range assumes plane bed conditions; see text for detailed explanation.

[3]High range incorporates bedform dimensions into channel roughness calculations; see text for detailed explanation.

[4]Estimate at MAL is determined by subtracting volumes of dredged and mined sediment from total estimated bedload at SJJ and SRV; it does not factor in potential settling of additional sediment from suspension in that reach.

[5]Negative values suggest a deficit of sediment and do not imply landward transport; see text for details.

Table 1.2. Estimated annual total sediment and sand-sized sediment entering Suisun Bay from the Sacramento-San Joaquin Delta at Mallard Island (U.S. Geological Survey Station 11185185, California Department of Water Resources Station MAL).

[Mt/yr, million metric tons per year]

Water year	Estimated net total bedload at MAL[1,2] (Mt/yr)	Estimated net sand bedload at MAL[2] (Mt/yr)	Total suspended sediment at MAL (Mt/yr)	Suspended sand at MAL (Mt/yr)	Total sediment flux at MAL (Mt/yr)	Sand sediment flux at MAL[2] (Mt/yr)
2001	−0.308	−0.271	0.264	0.008	−0.044	−0.263
2002	−0.135	−0.119	0.310	0.009	0.175	−0.11
2003	−0.109	−0.096	0.547	0.016	0.438	−0.08
2004	0.018	0.016	0.640	0.019	0.658	0.035
2005	−0.029	−0.026	0.429	0.013	0.4	−0.013
2006	−0.145	−0.128	1.41	0.042	1.265	−0.086
2007	−0.045	−0.040	0.125	0.004	0.08	−0.036
2008	−0.191	−0.168	0.218	0.007	0.027	−0.161
2009	−0.019	−0.017	0.159	0.005	0.14	−0.012
2010	−0.031	−0.027	0.314	0.009	0.283	−0.018
2011	0.125	0.110	0.602	0.018	0.727	0.128
2012	0.118	0.104	0.190	0.006	0.308	0.11
2013	0.091	0.080	0.291	0.009	0.382	0.089
2014	0.074	0.065	0.096	0.003	0.17	0.068
2015	−0.073	−0.064	0.191	0.006	0.118	−0.058
2016	−0.079	−0.070	0.504	0.015	0.425	−0.055
2017	0.682	0.600	2.17	0.065	2.852	0.665
2018	−0.167	−0.147	0.226	0.007	0.059	−0.14
2019	0.061	0.054	0.824	0.025	0.885	0.079
2020	−0.105	−0.092	0.122	0.004	0.017	−0.088
Total	−0.267	−0.236	9.632	0.290	9.365	0.054
Mean	−0.013	−0.120	0.482	0.015	0.469	0.003

[1]Bedload transport in million cubic meters per year (Mm^3/yr) in table 1.1 was converted to Mt/yr using a conversion factor of 1,517 kilograms per cubic meter; see text for details.

[2]Negative values suggest a deficit of sediment and do not imply landward transport; see text for details.

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