San Francisco Estuary Regional Monitoring Program for Trace Substances

Estimates of Suspended-sediment Flux Entering San Francisco Bay from the Sacramento and San Joaquin Delta

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Abstract

This report was written at the request of the Sources Pathways and Loadings Workgroup (SPLWG) of the San Francisco Bay Regional Monitoring Program (RMP) for Trace Substances. It demonstrates the use of suspended-sediment concentration (SSC) data collected by the U.S. Geological Survey (USGS) at Mallard Island as a means of determining suspended-sediment flux entering San Francisco Bay from the Sacramento and San Joaquin River watersheds. In addition, the data and analysis will be used in future studies for estimating particle-associated contaminant fluxes for mass budget calculations to help fulfill the objectives of the Regional Water Quality Control Board Regions 2 and 5. The data were collected during water years (WYs) 1995 to 1998. SSC data were estimated by the USGS using regression relationships between SSC and optical backscatter (OBS) data recorded every 15 minutes. Daily fluvial advective sediment flux was estimated by combining estimated Delta outflow with daily averaged SSC data. On days when no data were available, sediment flux was estimated using linear interpolation. A model was developed to estimate fluxes associated with tidal advection and dispersion using velocity and SSC data collected during a more restricted period (WYs 1994 and 1996). This model then was used to correct the positive bias that would have occurred if tidal forces had not been considered. In addition, the total error associated with the determination of loads was quantified by considering the following sources of error: daily averaging of SSC data, Delta outflow, laboratory analysis of SSC, regressions between SSC and OBS, and variation of SSC in the cross-section of the water column; total error was ± 17 percent.

Annual discharge during WYs 1981 to 2000 varied from 5x10^3 Mm^3 (million cubic meters) to 80x10^3 Mm^3 [coefficient of variation (CV) = 0.81]. Mean annual discharge for WYs 1995 to 1998 was wetter than average, 45x10^3 Mm^3 compared to 26x10^3 Mm^3 for WYs 1981 to 2000. On average, 85 percent of the annual Delta outflow occurred during the wet season (December 1 to May 31). SSC at Mallard Island was highly variable, ranging from 5 mg/L (milligrams per liter) to 420 mg/L during the study period. On an annual basis, dispersive flux caused an upstream sediment flux of about 0.39 Mt (million metric tonnes) during WY 1995, 0.23 Mt during WY 1996, 0.34 Mt during WY 1997, and 0.40 Mt during WY 1998. Thus, if tidal effects had not been taken into account, sediment flux from the Central Valley to the Bay would have been over estimated by an average of 0.34 Mt per year or about 14 percent during WYs 1995 to 1998. Taking fluvial and tidal forcing into account, on average, 90 percent of the annual suspended-sediment flux was discharged through the Delta during the wet season of a given WY, and 46 percent occurred during the wettest 30-day period. For example, the January 1997 flood transported 1.2 Mt of suspended sediment or about 15 percent of the total 4-year flux (8.3 Mt). Annual suspended-sediment flux at Mallard Island averaged 2.1± 0.3 Mt. Given that the average water discharge for the 1995-98 period was greater than the average discharge for the last decade, it seems likely that the average suspended-sediment flux may be less than 2.1± 0.3 Mt. The average flux calculated for Mallard Island was less than previous estimates by a factor of two, supporting previous studies that indicated a decreasing trend of sediment flux on the Sacramento River.

These results have implications for management of the Bay. For example, decreasing suspended-sediment loads may be one of the factors that influence erosion and redistribution of sediments in the Suisun and San Pablo Bay segments and, thus, affects the transmission of contaminants from the sediment to the water column. If loads of suspended sediments (and contaminants) entering the Bay from the Central Valley are of lesser magnitude now than in the past, this implies that loads from point sources, atmospheric deposition, dredged material and small local tributaries may be increasingly important in the overall sediment and contaminant

budgets of the Bay. Finally, if sediment loads are decreasing over time, there may be less sediment available for restoration projects, and sensitive areas on the Bay margins, such as mud flats and fringe marshes, may begin to erode.

From an RMP perspective, the most relevant application of SSC data and the improved estimates of sediment flux provided here is to improve the understanding of the timing and magnitude of sediment-associated contaminants of concern that enter the Bay from the Central Valley. Scientific work needed to provide this understanding includes:

1. *Analysis of SSC data collected at Mallard Island to estimate sediment flux to the Bay from the Delta and*
2. *Expansion of data collection and analysis to include contaminants of concern using the following steps:*

a) *Work with the California Department of Water Resources (DWR) to gain an understanding of the errors in magnitude and timing of estimated Delta outflow from the DAYFLOW Model. This may include modeling discharge in hourly time steps to better assess the effects of short time-scale variations in SSC on estimates of loads.*
b) *Continue to use Mallard Island SSC data to estimate loads on daily, flood, monthly, and annual time steps during subsequent years of data collection to WY 2004. By 2004, there will be 10 years of data that will allow an accurate understanding of intra- and inter-annual flux dynamics of sediment entering San Francisco Bay from the Delta.*
c) *Consult with other scientists who have specialized knowledge in the collection and analysis of particle-associated contaminants. Determine an appropriate sampling design for gathering data suitable for developing regression equations between OBS measurements at Mallard Island and inorganic and organic particle-associated contaminants of concern.*
d) *Collect water samples with a focus on flood flow conditions at Mallard Island using the study design determined in Step c and analyze these for sediment particle-associated contaminants including metals, PCBs, PAHs, and historically used pesticides, as deemed necessary by the SPLWG of the RMP.*
e) *Collect additional samples or analyze existing data to better determine the vertical and lateral variability of suspended sediment in the water column at Mallard Island to determine whether point data collected at the edge of the channel is representative of the whole water column.*
f) *Develop relations between concentrations of sediment-bound contaminants and OBS.*
g) *Estimate continuous contaminant-concentration data for Mallard Island and combine these data with discharge estimates to determine contaminant flux entering the Bay from the Delta.*

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Introduction

The Technical Report of the Sources Pathways and Loadings Workgroup (SPLWG) for the San Francisco Bay, Regional Monitoring Program for Trace Substances (RMP) (Davis *et al.*, 1999) outlined recommendations for redesigning the RMP to specifically satisfy the objectives and management questions established for the program. Because there is a strong relation between sediment loads and transfer of contaminants to the Bay, such as metals, PCBs, PAHs, and chlorinated pesticides, one of the high priority recommendations (and the purpose of this report) was to conduct an information review and analysis of available suspended-sediment data for the Sacramento and San Joaquin Rivers (Figure 1). The specific purpose was to

> ***Obtain information on sediment transport during large resuspension events and estimate contaminant loading. Identify information gaps that can be addressed by field sampling.***

Objectives

This report directly follows this recommendation by providing a review of available information on sediment dynamics in the Delta, analyzing the available suspended-sediment concentration (SSC) data, and estimating loads of suspended sediment for the water years (WY) 1995 – 1998 (a WY is from October 1 to September 30 and is denoted by the year of the end date). Loads of contaminants are not estimated due to the lack of suitable data. Methods for filling gaps in information are provided.

Review of current knowledge of sediment dynamics in the Delta

A substantive body of knowledge already exists on water and sediment transport and circulation in the Delta. Many factors have been identified that influence SSC, including human activities, storms, tides, wind, channel hydrodynamics, salinity, and flow barriers and diversions. The question of how these factors influence the accuracy and precision of flux estimates should be considered during review of these results. Although sediment flux during high flow periods is likely to overwhelm the effects of tides, wind, channel hydrodynamics, salinity, and flow barriers and diversions, the effects of dispersive (and tidally advective) processes were considered in this study.

Human activities over the past few centuries have greatly modified or overwhelmed the natural sediment processes in the Sacramento and San Joaquin River systems. Hydraulic mining in the Sierra foothills during the Gold Rush era dramatically increased the supply of sediment to the fluvial system (Krone, 1996). Prior to 1850, the tributary rivers delivered about 1.3×10^6 m^3 of sand and gravel to the Central Valley floor annually, but between 1860 and 1884, the annual load increased five-fold, to about 6.5×10^6 m^3 (Kondolf, 2000). Part of this delivered sediment still is being resuspended and transported through the Delta. In addition, soil disturbance and erosion from agricultural activities and urbanization also has increased the supply of sediment to the Sacramento and San Joaquin Rivers in the years since the Gold Rush.

Since at least the 1950s, human influences have caused a net decrease in sediment flux. Many of the tributary rivers in the Central Valley have been dammed for irrigation and water supply. Greater than 95 percent of the reservoir storage capacity has been built since 1921, and exports of water out of the Delta tributaries commenced in 1929 (Fox *et al.*, 1990). The literature supports seasonal flow regime shifts during the past 80 years. Fox *et al.* (1990) concluded that the effects of land use and other human alterations, such as water export, have had less influence on annual discharge than climatic effects, and annual discharge actually has increased with time. However, these and a number of other conclusions and inferences made by Fox *et al.* (1990) were contested (Helsel and Andrews, 1991; Williams, 1991). Delta outflow has decreased in April and May and increased from July to November (Fox *et al.*, 1990; Dettinger *et al.*, 2001; Knowles, 2001). Additional recent work implies that annual variations in Delta outflow due to climate have kept pace with the effect of human alterations, but there has been no statistical increase over the long term (Knowles, 2001). Reservoir storage ($3.5x10^9$ m^3) is equivalent to 80 percent of the mean annual runoff in the Sacramento Basin, and winter floods have been reduced by 40 – 90 percent, reducing the bed and suspended load-transporting capacity (Kondolf, 2000). Reductions in stream power are likely to have reduced bed load in Central Valley streams by a greater proportion than suspended-sediment loads (James McGrath, Port of Oakland, oral comm., December 2001). Additionally, coarser sediments are stored in large volumes behind Central Valley reservoirs, and large volumes of water and sediments are extracted from the Delta each year, thereby changing the hydrodynamics and sediment transporting capacity within the Delta itself. Sediment sinks in the Delta associated with the abandonment of Delta islands also may reduce sediment transport to the Bay from the Delta (Phillip Williams, Phillip Williams & Associates, oral comm., March 2002). Reductions in peak annual discharge and changes in the seasonal flow regime, as well as the trapping of sediments behind reservoirs and Delta sinks, have led to reductions in the natural flow of sediments entering San Francisco Bay via the Delta system (Krone, 1979).

SSCs in Delta outflows increase with discharge associated with storm rainfall and storm flows (Ruhl and Schoellhamer, 1998). SSCs rise and peak during the rising limb or near the peak of the flood hydrograph. Within the weeks following a discharge peak, SSCs return nearly to preflood concentrations. There is a marked first-flush effect, such that during subsequent floods (within the same water year), peak sediment concentrations are less than that of the first flush, even when discharge is similar or in some cases greater (Goodwin and Denton, 1991; Ruhl and Schoellhamer, 1998; Oltmann *et al.*, 1999).

SSCs also vary in response to tidal advection and tidal resuspension. There also is bimonthly variation associated with the spring-neap tidal cycle (Schoellhamer, 1997). Schoellhamer (1997) found that about one-half of the variance in SSCs was caused by the spring-neap cycle and that the pattern of concentration lags behind the cycle by about 2 days. Longer periods of slack water during the neap tides allow greater deposition, whereas suspended sediments accumulate in the water column as spring tides approach (Schoellhamer, 1997). During high-flood discharge, the tidal effect remains evident at Mallard Island (e.g., January 1997 flood). Even on the day that recorded the highest discharge, the flood tide caused velocity to reduce to almost slack water. During smaller floods, slack water usually is attained and there usually is a period of reverse flow (David Schoellhamer, USGS, unpublished data, 2001). During the 1996 floods, SSCs at Mallard Island were influenced by local deposition during slack water and resuspension again as the tide changed, resulting in as many as four peaks in SSCs in 1 day (Jennings *et al.*, 1997).

In addition to tidal variations, there also are seasonal variations in response to wind-wave action and associated wind shear stress at the sediment-water interface (Krone, 1979; Schoellhamer, 1997; Ruhl and Schoellhamer, 1998). This facet of the annual variation has been attributed to unconsolidated bottom sediments being resuspended when wind increases during the spring and summer months. The effect reduces in magnitude as the summer progresses, and sediments consolidate and coarsen due to selective winnowing and transport of fines. The magnitude of the wind-wave effect varies greatly in response to water depth, currents, and wind shear (Ruhl and Schoellhamer, 1998).

SSCs also vary throughout the cross section of the river channel; sediment concentrations and residual flow may differ throughout the water column (Schoellhamer and Burau, 1998). Tidally averaged currents and sediment transport can have a net landward direction near the bottom and a net seaward direction in the upper water column due to salinity gradient-induced gravitational circulation. In areas of stratified bi-directional flow, a "null zone" often exists that generally is associated with maximum turbidity. Gravitational circulation results in near-bottom pulses of landward flow and salt but very little sediment (Schoellhamer and Burau, 1998). Although it is likely that the geographic location and vertical position in the water column where suspended-sediment data are collected may affect the measured concentrations, the error probably is small (David Schoellhamer, USGS, unpublished data, 2001).

Salinity influences SSC and deposition by increasing cohesion and turbulence, forming aggregates, and increasing settling velocities (Krone, 1979; Schoellhamer and Burau, 1998). Delta outflows are managed to repel salt intrusion due to the tides during the drier summer months (Ogden Beeman & Associates, Inc., 1992). This also helps regulate bottom salinity in Suisun Bay to maintain a desired estuarine salinity gradient (salinity influences the species of animals and plants that live in the Bay) (Jassby *et al.*, 1995; Schoellhamer and Burau, 1998; Joshua Collins, San Francisco Estuary Institute, pers. comm., February 2001). Salt intrusion into the Delta varies by year and season, depending on Delta outflow. The maximum limit of salt intrusion in the last decade has been at least 15 km upstream from Pittsburg; earlier this century salt intruded farther than 40 km upstream from Pittsburg (Department of Water Resources, 1995). During larger floods, however, the saline mixing zone extends from the Golden Gate to Carquinez Strait and, therefore, it may be inferred that the majority of sediment delivered through the Delta from the Central Valley is transported into or through the Bay.

Mixing and flow distribution in the Delta are highly influenced by artificial flow barriers and diversions. For example, opening the Delta Cross Channel significantly increases the amount of lower-salinity Sacramento River water that reaches the southern Delta. Installation and removal of barriers in the southern Delta strongly influence the flow patterns and distributions of San Joaquin River water in the southern Delta (Paulsen and List, 2000). Paulsen and List (2000) also found that during the 1997 flood, sources of water from inside the Delta had an effect on the water quality of Delta outflows.

Materials and Methods

Physical description

The channel adjacent to Mallard Island conveys runoff from 154,000 km^2 [>37 percent of the land area of California (411,000 km^2)]. The Delta itself covers a land area of 3,000 km^2 and incorporates hundreds of kilometers of waterways and thousands of kilometers of levees. The majority of the peat soils in the Delta are less than 3 m thick, but in some areas, peat soils are as thick as 20 m. Most of the Delta is below sea level; some areas are greater than 5 m below sea level. Reclaimed lands in the Delta are continuing to subside due to compaction, dewatering, and oxidation of peat soils that release carbon dioxide. There are about 1,800 agricultural diversions for water in the Delta, and at peak summer irrigation there may be greater than 113 m^3/s of water draw (Department of Water Resources, 1995). Some agricultural drainage water is pumped back to the adjacent canals, which returns salts, minerals, and other residues that affect water quality.

Development of the Delta began in 1850 with the Swamp and Overflow Land Act. By 1869, levees had been constructed on Sherman Island. The peat soils that were used turned out to be poor material for levee construction; oxidation, compaction, and subsidence of the peat contributed to levee failure. Dredging of the waterways began in the late 1870s, improving the transmission of water (Department of Water Resources, 1995). Although most of the waterways in the Delta system are modified natural sloughs, many additional channels have been constructed and dredged for navigation, water circulation, and to provide construction materials. There are two deepwater channels, one running east from Browns Island to Stockton on the San Joaquin River and the other running north of Browns Island up the Sacramento River to Rio Vista and then via the Sacramento Deep Water Ship Channel to Sacramento. In addition, during high flows, flood waters are diverted north of Sacramento though the Yolo Bypass. This artificial plumbing system is the conduit for water and sediment between the Central Valley and San Francisco Bay.

Suspended-sediment data

SSC data analyzed in this report were collected at Mallard Island (Figure 1) from February 9, 1994, to September 30, 1998 (1,695 days) (Buchanan and Schoellhamer, 1996, 1998, 1999; Buchanan and Ruhl, 2000). The channel depth at the Mallard Island gage is approximately 7.6 m, while the adjacent shipping channel has a depth of about 17 m and an average tidal range of 1.25 m. Data were collected every 15 minutes, giving as many as 96 data points per day. As a result of equipment malfunction, biological fouling, and vandalism, only 877 days of data (52 percent) were fully retained in the record. Greater than 25 percent, or 24 out of 96 data points, were recorded on about 72 percent of the days. A total of 465 days, or 27 percent of the potential days on record, had no data. The data were collected 1 m below the water surface using an OBS instrument calibrated with discrete water samples collected and analyzed for SSC (e.g., Buchanan and Ruhl, 2000). Data also were collected at 2 m above the base of the channel at Mallard Island.

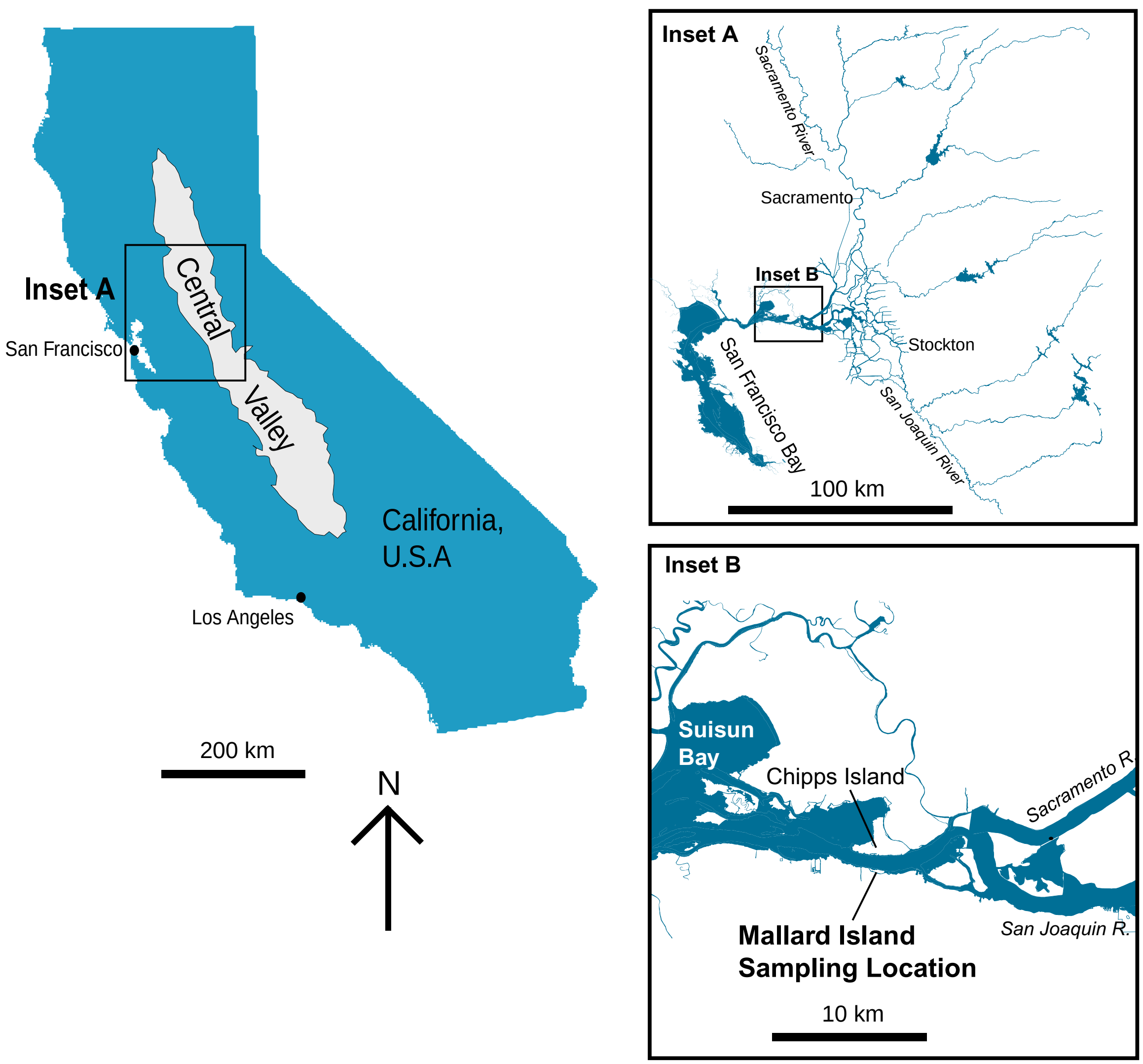

Figure 1. The Mallard Island sampling location.

However, the surface data are the most continuous and likely the most representative of average water column concentrations (David Schoellhamer, USGS, unpublished data, 2001). There has been discussion (in regard to collection methods and laboratory analysis) on whether the data collected are “suspended-sediment concentrations” or “total suspended solid concentrations” (Gray *et al.*, 2000). The use of the term "SSC" in this report conforms to the methods outlined in Buchanan and Ruhl (2000) and the current policy of the USGS.

Hydrology

Given that water circulation at the Mallard Island site is tidally influenced, the net (tidally averaged) discharge cannot be gaged using standard hydrological techniques for riverine discharge, such as the area-velocity method. Instead, discharge is estimated at Mallard Island by the DWR (Interagency Ecological Program, 2001a) using a mass-balance approach and the DAYFLOW model. As the term "DAYFLOW" suggests, the Delta outflow estimates have a time interval of 1 day but do not include variation due to the spring-neap cycle. DAYFLOW data are available for 1956 to the present from the Interagency Ecological Program (IEP) (Interagency Ecological Program, 2001b). Delta outflow estimated using the DAYFLOW Model is the longest-running record of water discharge entering San Francisco Bay from the Delta. Tidal gage height data have been measured at Mallard Island since 1900 and are available from the DWR.

Flux calculation

The total residual flux [F] of a given constituent can be decomposed into eleven terms (Dyer, 1974) as follows:

$$[F] = [[A]]\,[U_a]\,[C_a] + [[A]]\,[U_a'C_a'] + [A'U_a']\,[C_a] + [A'C_a']\,[U_a] + [A'U_a'C_a'] + [[A]]\,([U_{dt}][C_{dt}])_a + [[A]]\,([U_{dv}][C_{dv}])_a + [[A]]\,([U_t'C_t'])_a + [[A]]\,([U_v'C_v'])_a + [A'(U_t'C_t')_a] + [A'(U_v'C_v')_a], \quad (1)$$

where A = area
U = velocity
C = concentration

Brackets indicate a tidally averaged value, and the prime denotes the deviation of the instantaneous value from the tidally averaged value. The subscript $_a$ indicates a cross-sectionally averaged value, while subscript $_v$ specifies a vertical average, and $_t$ a transverse average. Subscript $_{dv}$ is the deviation of the depth average at any position from the cross-sectional average, and $_{dt}$ the deviation of the average value at any depth from the depth-averaged value. The terms describe the contribution of various forcings to the total flux. In their respective order they are (1) the flux contribution of river discharge (advective flux), (2) correlation between fluctuations of velocity and concentration (dispersive flux), (3) inward transport of the progressive tidal wave, (4) correlation between tidal height and concentration, (5) third-order correlation of tidal height, velocity and concentration, (6) net transverse circulation, (7) net vertical circulation, (8) transverse oscillatory shear, (9) vertical oscillatory shear, (10) covariance of cross-sectional area fluctuations with the transverse oscillatory shear, and (11) covariance of cross-sectional area fluctuations with the vertical oscillatory shear (Dyer, 1974).

Simplifications and assumptions

Limitations of the data set preclude solving each term in the flux equation. The variable that accounts for the fluctuation in area is unknown, which prohibits calculation of an exact solution. The cross-sectional variability in the velocity and concentration fields also is unknown. Term 1 (advective flux) is the only term that can be estimated over the desired timescale in this study, though simplification of that term also is required.

Advective flux

Given the constraint of a daily time interval for estimated discharge, daily advective flux was estimated using the following equation:

$$\text{Daily advective flux} = C_{av}DF \qquad (2)$$

where C_{av} is the average SSC for a 24-hour period and DF is the discharge of water estimated using the DWR DAYFLOW model for the same period. SSC data [milligrams per liter is equivalent to tonnes per million cubic meters (mg/L = t/Mm^3)] were combined with daily discharge [million cubic meters (Mm^3)] to give the advective flux of suspended sediment in metric tonnes (t). On days with no suspended-sediment data, flux was estimated by linear interpolation. SSC was estimated by interpolating across the data gaps, and the flux was estimated by multiplying the estimated SSC by daily discharge. Interpolation of the SSC data was preferred to interpolating between flux measurements because the latter estimate retained the variation associated with discharge. The method assumes that the point SSC data at Mallard Island is representative of the entire cross section. While lateral and vertical structure of the concentration profile is unknown, it is reasonable to assume that during high-flow events (when most of the sediment is delivered), the cross section at Mallard Island is well mixed due to high velocities. During low-flow events, this may not be the case, due to stratification effects, flood/ebb asymmetries, and other phenomena.

Neglected flux terms

Estimating the total residual flux at Mallard Island as the product of daily DAYFLOW discharge and mean concentration neglects several terms from the total flux equation. The magnitude of the first four terms of the flux equation can be estimated via point data at the Mallard Island site. This method estimates the bias produced when the advective flux estimate alone is used to compute total flux, though the time variation of cross-sectional area must be ignored due to a lack of data. The remaining terms cannot be estimated due to a lack of cross-sectional velocity and concentration data.

Term 2 of the flux equation represents the residual dispersive flux, which can be significant in many systems. Dispersive flux essentially is a measure of the correlation between tidal velocity and sediment concentration. The relative contributions of advective and dispersive flux to the total flux were estimated using point velocity and concentration data at Mallard Island. While the units of these point-fluxes (mass per unit area and time) are not congruent with the units of advective flux in the full flux equation (mass per unit time), the exercise here is to estimate the bias involved in computing only an advective flux. Although dispersive flux is likely to be small during high flow periods, it likely is large during the rest of the annual cycle when tidal flushing is dominant. Therefore, the simplified point-flux equation, neglecting the last seven terms of the fully developed flux equation, as well as cross sectional area variations, is as follows:

$$[f]=[[u][c]] + [u'c'] + [[u]c'] + [u'[c]] \qquad (3)$$

where $[[u][c]]$ is the residual advective flux and $[u'c']$ is the residual dispersive flux. All terms are analogous to terms 1 – 4 in the full flux equation. This equation was applied to point velocity and SSC data at Mallard Island.

Three sets of data were available for this analysis; one from WY 1996 (near-surface), and two from WY 1994 (near-surface and mid-depth). An ADCP was deployed near the gage house where SSC data were collected 1 m below the water surface and at mid-depth. The ADCP measured velocity in vertical bins, and flux was calculated using the bin closest to the elevation of the optical sensor used to measure SSC. Here we calculate point-flux rather than cross-sectionally averaged flux, which is valid for comparing advective and dispersive flux.

Mid-depth SSC data were not collected during WY 1996 deployment due to vandalism. The ADCP deployments during WYs 1994 and 1996 were at different locations; therefore, the total flux cannot be compared between the deployments.

For illustrative purposes, cumulative frequency of flow during WY 1996 are used to identify high, average, and low-flow periods. Flows above the 90 percent cumulative frequency (2,747 m^3/s) are considered high, flows at 50 percent (396 m^3/s) are considered average, and flows below 10 percent (226 m^3/s) are considered low.

Combining advective and dispersive flux estimates

To correct the positive bias associated with calculating advective flux alone, for WYs 1995 – 1998, an equation was fit to the scatter of points created by plotting Delta outflow versus the ratio of dispersive to advective flux for the available data. This was achieved using the following methodology: a fit of the form $r=Aq^B$ was desired, so as q approaches infinity, r approaches zero; and as q approaches 0, r approaches negative infinity. The log was applied to both sides, generating [log r=log A + B log q]. The line [r=mq+b] was generated, where m is analogous to B, and 10^b is analogous to A. The log transform was applied to all values, and all five positive points were eliminated. The remaining values were converted to positive values. Using the variables ratio (r), and Delta outflow (q), log (q) was plotted versus log (r). A linear least squares regression was fitted to the plot. With the resulting fit, [r=mq +b], $A=10^b$, B=m. The linear fit resulted in m=-0.398, A= 3.334. The values were converted back to negative values, and A was changed to -A. The five positive values were reinstated on the plot so that their existence was not ignored, even though they were not included in the fit.

Error analysis

SSC data were averaged for each day (up to 96 data points per day). To determine the error associated with taking the average over the tidally affected 24-hour record, the SSC data were filtered using a low-pass filter with a cutoff period of 30 hours. The record then was integrated daily, and divided by 96 (number of readings per day) to get a filtered, daily integrated average concentration (cf_{ave}). The mean daily concentrations from the same record (c_{ave}) were used to calculate the percent difference between the filtered average and the daily geometric average [$(cf_{ave}-c_{ave})/cf_{ave}$]. The percent differences were squared, summed, and the square root taken to give an rms error of 0.67 percent.

The error in Delta outflow will be the error associated with all the parameters that are used in the DAYFLOW calculation. The DAYFLOW Delta outflow has been compared to measurements of outflow based on ultrasonic velocity meters (UVM) (Oltmann, 1998). Oltmann found that during the period of high flow that he tested (winter 1996), the two hydrographs matched "fairly well". Given the difficulty with estimating some of the input terms in the DAYFLOW calculation, especially during low flow when water use for drinking and irrigation dominate the calculation (Interagency Ecological Program, 2001a) and when the spring and neap tides effectively empty and fill the Delta (Oltmann, 1998), an error of at least ±5 percent is likely. The error associated with laboratory analysis of SSC was set at ±5 percent (Gray *et al.*, 2000). The estimated error associated with the regression between OBS and SSC was ±10 percent [see regressions in Buchanan and Schoellhamer (1996, 1998, 1999) and in Buchanan and Ruhl (2000)].

The heterogeneity of SSCs in the water column is a potential error in the study calculations. At this time, data collected near the base of the deep-water channel at Mallard Island (Buchanan and Schoellhamer, 1996, 1998, 1999; Buchanan and Ruhl 2000) have not been included in this analysis. During WY 1995, Buchanan and Schoellhamer (1996) found that mean near-surface SSC was 43 mg/L and the near-bottom SSC was 41 mg/L (a difference of -5 percent). During WY 1996, Buchanan and Schoellhamer (1998) noted that mean near-surface SSC was 42 mg/L and the near-bottom SSC was 55 mg/L (a difference of +27 percent). During WY 1997, Buchanan and

Schoellhamer (1999) noted that mean near-surface SSC was 48 mg/L and the near-bottom SSC was 54 mg/L (a difference of +11 percent). During WY 1998, the near-bottom concentrations were +2 percent greater than the near-surface concentrations (Buchanan and Ruhl, 2000). In years when the near-bottom concentrations are greater than the near-surface concentrations, a negative bias in flux estimation would result during high-flow periods when discharge throughout the water column is downstream (ebb flow). This negative bias may be offset partially by upstream transport of sediment during flood tides at drier times of the year (e.g., Tobin *et al.* 1995). The differences between top and bottom may be an overestimation of the error because not all the top and bottom data are concurrent. In any case, it seems that the error associated with water column heterogeneity either can be positive or negative and <5.5 percent (5.5 = 11/2) if it also is assumed that the representative concentrations are the average of the near-surface and near-bottom concentrations. Further, if it is assumed that lateral variations are similar to the vertical, then the total error associated with water column variation will be ±11 percent. The errors (shown in Table 2) were calculated as follows:

$$\text{Error} = (0.67^2+5^2+5^2+10^2+11^2)^{0.5}$$
$$= \pm 17 \text{ percent}$$

It is assumed that the error calculated in this manner is representative of all four water years. The error was also applied to flux calculated for days when no SSC data were recorded.

Results

Delta outflow for water years 1995 – 1998

DAYFLOW estimates followed an intraannual cycle typical of Californian Mediterranean (dry summer subtropical) climate, which is dominated by winter flow (Figure 2). The "wet season" during WY 1995 to WY 1998 started in December and ended 3 – 6 months hence. For consistency, however, the wet season of each water year was considered December 1 to May 31. On average (WYs 1995 – 1998), 85 percent of the Delta outflow occurred during the wet season and >30 percent occurred during the wettest 30-day period of each year. Discharge varied interannually from 31×10^3 Mm^3 in WY 1996 to 54×10^3 Mm^3 in WY 1998. This relatively small interannual variation does not reflect long-term variability. Discharge during WYs 1981 – 2000 varied from 5×10^3 Mm^3 to 80×10^3 Mm^3 (16 times) with a coefficient of variation (CV) of 0.81. Mean annual discharge for WYs 1995 – 1998 was greater than average (45×10^3 Mm^3 compared to 26×10^3 Mm^3 for WYs 1981 – 2000 or 27×10^3 Mm^3 for WYs 1991 – 2000). Furthermore, discharge was below average during an 8-year drought from WYs 1987 – 1994. This may have decreased the net transport of sediment during those years and increased the amount of storage in channels and watershed surfaces that subsequently could be eroded or resuspended during later years when flow increased.

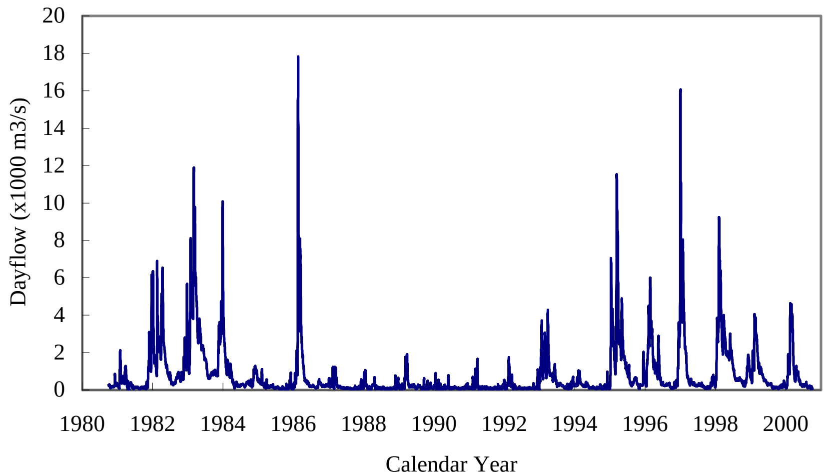

Figure 2. Daily water discharge (Delta outflow) at Mallard Island using output from the Department of Water Resources DAYFLOW model.

SSC and daily suspended-sediment flux at Mallard Island

SSCs at Mallard Island were highly variable, ranging from 5 mg/L to 420 mg/L. Fluvial advective discharge of suspended sediment at Mallard Island reflected the intraannual cycle to water discharge (Figure 3). Dispersive point-flux (flux estimated from point measurements and assumed to be representative of the entire water column) was calculated for the period for which data were available (Figure 4, December 17, 1995 – March 5, 1996, near-surface, high Delta outflow). During high flows, the advective point-flux dominates (Figure 4), which is expected because the large volumes of water moving seaward through the river are responsible for the transport of sediment. Dispersive point-flux magnitude averages about 11 percent of the advective point-flux magnitude during this above-average flow period (mean discharge=2,116 m^3/s). The direction of the dispersive point-flux mainly is in the opposite direction (landward) of the advective point-flux at the location of the Mallard Island station.

During a period of low flow (April 15, 1994 – June 4, 1994) (mean discharge = 255 m^3/s), the dispersive point-flux magnitude near surface averages about 49 percent of the advective point-flux magnitude, and almost always is in the opposite direction (landward) (Figure 5). For the same period, the mid-depth dispersive point-flux averages 52 percent of the advective point-flux. Thus, for lower flows, dispersive flux is relatively more important in estimating total flux. This result is similar to a scaling analysis of the relative magnitudes of the advective and dispersive flux, which calculates the two fluxes to be on the same order of magnitude for low flows (David Schoellhamer, USGS, unpublished data, 2001).

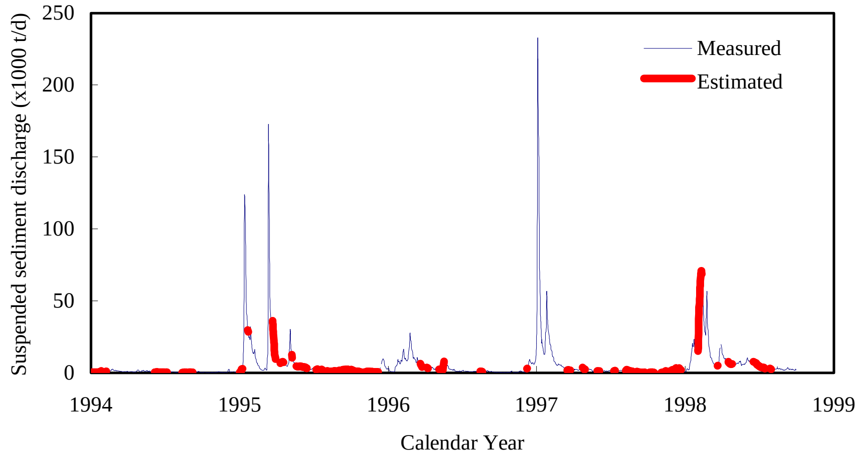

Figure 3. Daily fluvial advective suspended-sediment flux at Mallard Island. "Measured" refers to days for which suspended-sediment flux was calculated by combining Delta outflow and suspended-sediment concentration data. "Estimated" refers to days for which suspended-sediment flux was determined using linear interpolation.

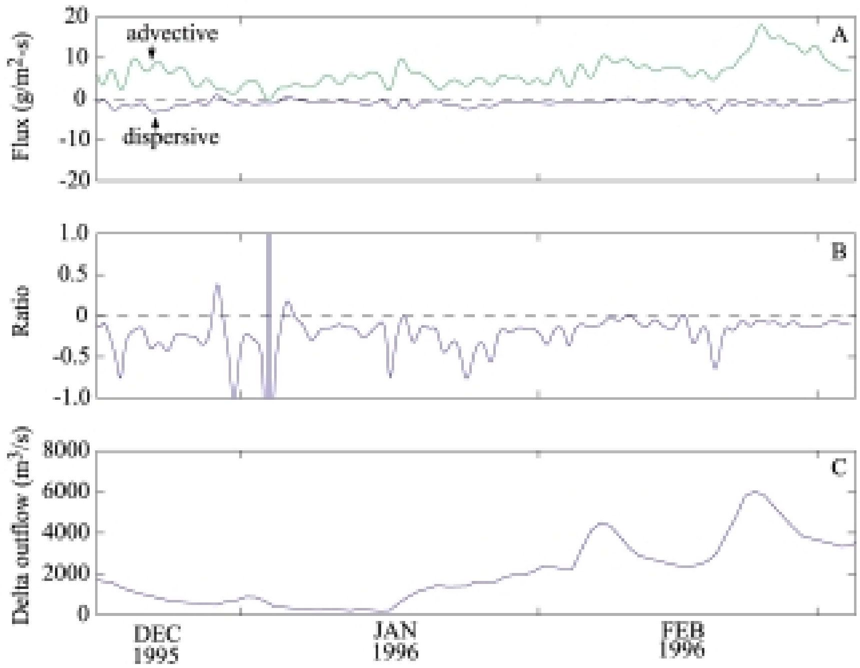

Figure 4. Advective and dispersive point-fluxes at Mallard Island (A), ratio of dispersive-to-advective point-flux (B), and Delta outflow (C), December 17, 1995 – March 5, 1996.

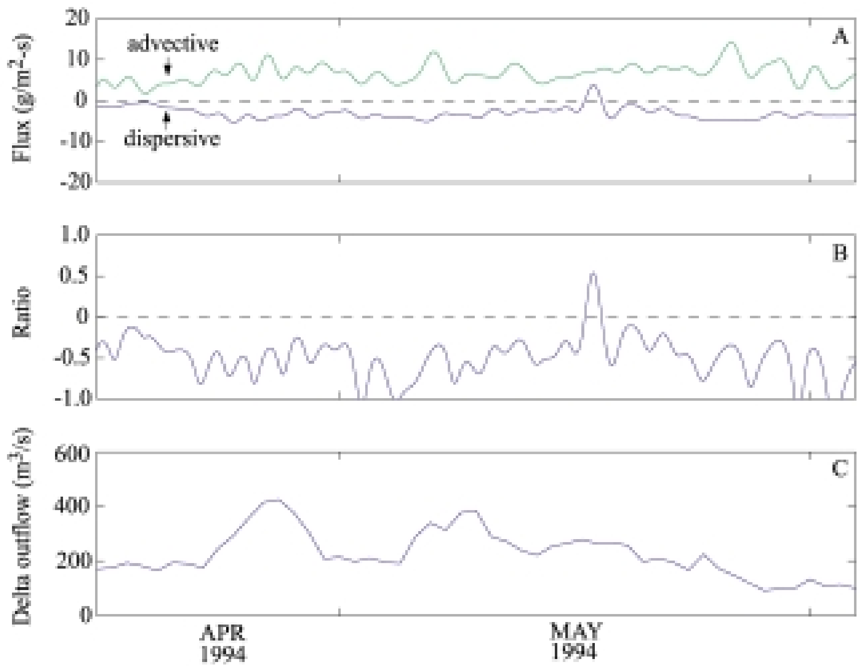

Figure 5. Advective and dispersive point-fluxes at Mallard Island (A), ratio of dispersive-to-advective point-flux (B), and Delta outflow (C), April 15, 1994 – June 4, 1994.

These results demonstrate that flux is overestimated at this location when only the advective term is considered, and the overestimate is largest during low-flow periods. However, the advective flux will be strongly dependent on flow, suggesting that at lower flows the overestimate of a small flux might not be as important to an estimate of the total annual sediment flux from the Delta to the Bay. Figure 6 presents the three data sets, displaying the flux that would be estimated by using only the advective term, and the total flux. The ADCP deployments were in different locations, so the flux cannot be compared directly between the WY 1994 and 1996 deployments.

The ratio of dispersive-to-advective flux was calculated and compared to Delta outflow (Figure 7). At infinitely high flows, the advective flux would be wholly responsible for transport, while at zero flow, the advective flux should go to zero, resulting in a dispersive/advective flux ratio of plus or minus infinity. The dispersive flux is rarely in the same direction as the advective flux at Mallard Island (points greater than zero).

Average dispersive point-flux for a given discharge was estimated using the curve shown in Figure 7. On an annual basis, tidal dispersive flux caused a net flow upstream of about 0.39 Mt during WY 1995, 0.23 Mt during WY 1996, 0.34 Mt during WY 1997, and 0.40 Mt during WY 1998. Thus, if tidal effects had not been taken into account, sediment flux to the Bay from the Central Valley would have been overestimated by an average of 0.34 Mt per year or 14.2 percent during WYs 1995 – 1998.

Dispersive fluxes for each discharge then were added to the advective fluxes to give the best estimate of suspended-sediment flux per day. While the use of point-flux data to estimate a bias in average cross-sectional flux may not be optimal, the analysis here shows that the dispersive flux must be considered even during high-flow periods. On average, (WYs 1995 – 1998) 90 percent of the annual flux (dispersive and advective) was discharged through the Delta during the wet season of a water year, 46 percent was discharged during the wettest 30-day period, 24 percent was discharged during the wettest 7-day period, and 5.2 percent of the suspended-sediment flux occurred on the wettest 1-day period (Table 1). The largest flood during WYs 1995 – 1998 occurred in January 1997. This flood alone transported 1.2 Mt of suspended sediment or about 15 percent of the total accumulated flux for the 4 years (8.3 Mt). When the second peak in January 1997 was included, 1.7 Mt of suspended sediment were transported, or about 20 percent of the 4-year total flux.

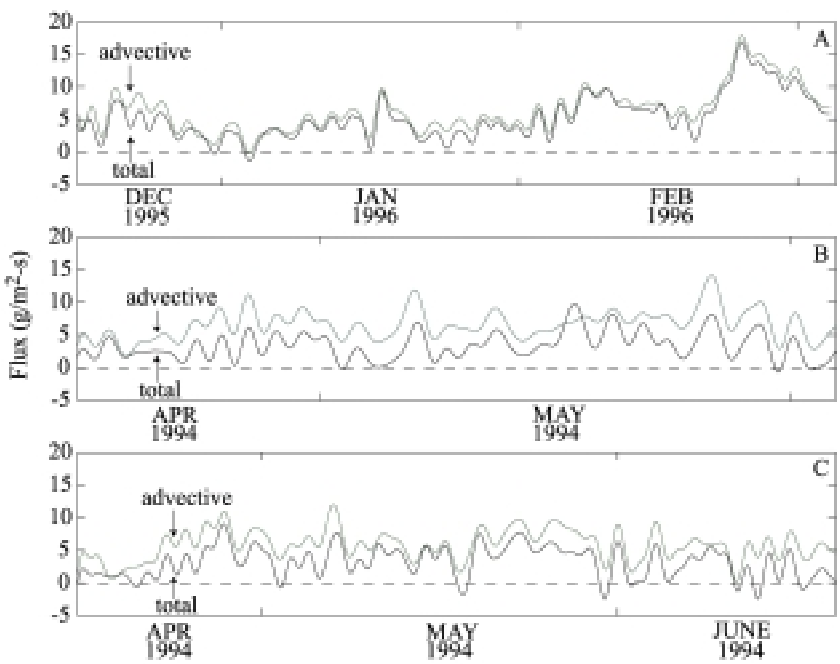

Figure 6. Comparison of advective and total point-fluxes at Mallard Island. December 17, 1995 – March 5, 1996, near surface (A), April 15, 1994 – June 4, 1994, near surface (B), and April 15, 1994 – June 20, 1994, mid-depth (C).

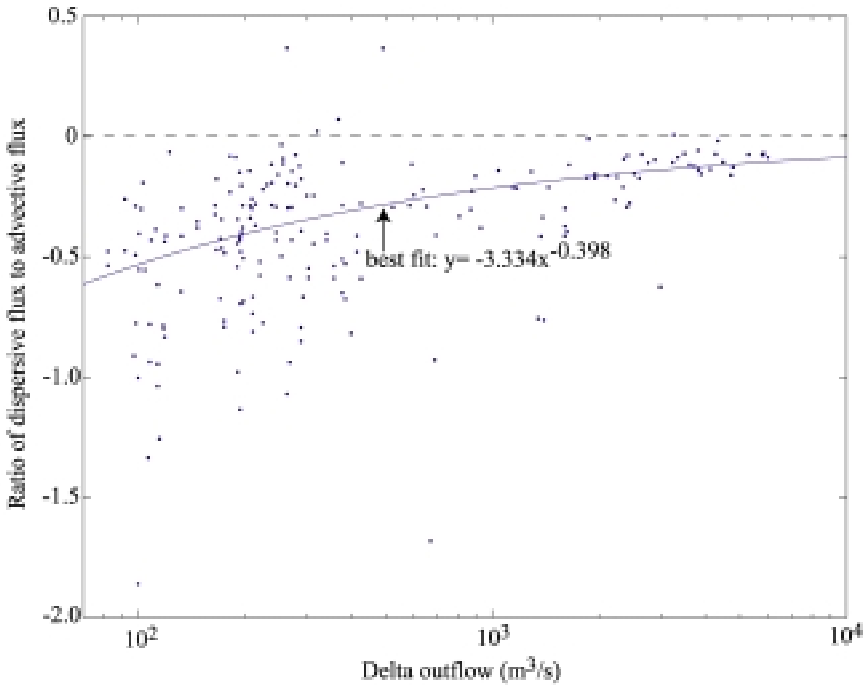

Figure 7. Ratio of dispersive-to-advective point-fluxes vs. Delta outflow, for all three data periods (198 points). A negative ratio indicates opposing directions of dispersive and advective point-fluxes.

Table 1. Intra-annual variation of the sum of advective and dispersive suspended-sediment flux at Mallard Island for water years 1995 – 1998. For example, during water year 1995, 22 percent of the total annual suspended-sediment flux was transported during seven consecutive days.

Water year	1 day (percent)	7 days (percent)	30 days (percent)	Wet season (percent) (December 1 to May 31)
1995	6.0	22	37	92
1996	2.5	13	35	88
1997	9.7	43	68	95
1998	2.7	17	45	83
Average	5.2	24	46	90

Annual suspended-sediment flux at Mallard Island varied from 1.0±0.2 Mt in WY 1996 to 2.6±0.4 Mt in WY 1995 and averaged 2.1±0.3 Mt (Table 2). Given that the water discharge for the 1995–1998 period was greater than the average discharge during the last decade, it seems likely that the average sediment flux may be less than 2.1±0.3 Mt. Water year 1996 had an average discharge and, therefore, WY 1996 suspended-sediment load

(1.0±0.2 Mt) may be the current best estimate of the average annual suspended-sediment load from the Central Valley to San Francisco Bay. However, it should be kept in mind that suspended-sediment load in a system is seldom linear, with respect to discharge. Water year 1996 followed a year of greater-than-average discharge that may have left the system low in stored sediment.

Table 2. Annual suspended-sediment flux at Mallard Island calculated for water years 1995 – 1998. Previous estimates are included for comparison. Unit conversions between metric units and English units were performed using 33 lbs/ft^3 for the dry unit weight of sediment (Krone, 1979) equivalent to 529 kg/m^3, 1 m^3 = 1.308 cubic yards (yd^3), and 1 metric tonne (t) = 1.102 short tons, therefore 1 million metric tonnes (Mt) = 2.47 million yd^3.

Author	Data calculation period	Annual suspended-sediment flux (Mt/y)	Annual suspended-sediment flux (Million cubic yards)
This study	1994/95	2.6 ±0.4	6.4±1.0
This study	1995/96	1.0 ± 0.2	2.5±0.4
This study	1996/97	2.2 ± 0.4	5.4±0.9
This study	1997/98	2.4 ± 0.4	5.9±1.0
This study	4-year average	2.1 ± 0.3	5.2±0.9
Krone (1979)	Average for 1960	3.0	7.5
Smith (1963)	?	*3.3	8.2
Schultz (1965)	?	*4.5	11.1
U.S. Army Corps of Engineers (1967)	?	*4.0	10.0
Porterfield (1980)	1909-66	*3.5	8.6
Ogden Beeman & Associates (1992)	1955-90	~2.8	~7.0

* These estimates include bed-sediment flux and suspended-sediment flux from local tributaries to San Francisco Bay as well as flux from the Central Valley.

Discussion

Suspended-sediment concentration and flow-data quality

Approximately 27 percent of the days between February 9, 1994, and September 30, 1998, had no data recorded. Given that the majority of the missing data occurred during low-flow periods (Figure 3), 83 percent of the flux was measured, and only 17 percent was estimated using linear interpolation. Only during the flood of 1998 were data missing on the rising stage of the hydrograph. In this case, 11 days were missing and linear interpolation was used to estimate the missing data. Although this may have caused an unknown, but significant, error (perhaps 10 percent in addition to the other errors) in the estimate of the flux for the 1998 water year, it certainly had little effect on the overall estimate of the average flux for the 4-year period.

In most studies of suspended-sediment flux, the discharge of water is measured on a smaller time interval than concentration. Thus, the scientific literature concerning measuring and estimating riverine flux is rich with methods that interpolate between concentration data points (e.g., Walling and Webb, 1981; Preston *et al.*, 1989; Kronvang and Bruhn, 1996). In contrast, the SSC data collected at Mallard Island have a time interval of 15 minutes (96 data points per day), and thus a potential loss in accuracy results from a 1-day time interval in water-discharge data. The travel time of a flood wave down the Sacramento and San Joaquin River systems may vary, depending on the back push of the daily and bimonthly tidal cycle, antecedent watershed and flow conditions, the magnitude of the rainstorm, and the peak intensity of the rainstorm. Given that the DAYFLOW model does not take into account factors such as these, the absolute timing of the peak flow may be imprecise. The 1-day time step for water discharge undoubtedly influenced the estimation of suspended-sediment flux at Mallard Island, but the loss of precision is perhaps random.

The use of the daily time step is satisfactory to estimate flux. Large floods pass through the Delta during periods of 7 – 14 days and the Delta is likely to “fill up” with water during floods. As discussed previously, Oltmann (1998) compared DAYFLOW Delta outflow with outflow based in ultrasonic velocity meters and found that the discharge during the 1996 wet season compared “fairly well”. Further, daily averaged SSC did not vary greatly between days during the January 1997 flood (35 mg/L to 45 mg/L). Therefore, as a consequence of the size of the system and the relatively low variability of SSC between days, the 1-day time step seems to be adequate for analysis of suspended-sediment loads. Additional work to test the use of models to generate flow on a smaller time step should be done to test this hypothesis.

Bidirectional flow (dispersive flux)

Tides at Mallard Island are mixed semi-diurnal. An example of tidal patterns at Mallard Island is shown in Figure 8. The tide range at Mallard Island is 1.25 m (mean lower low water to mean higher high water). The tide at Mallard Island is more attenuated than at other localities in northern San Francisco Bay. During large floods (e.g., January 1997), the tidal action at Mallard Island is not completely damped (Figure 9). It also can be seen that during the falling stages of the flood event hydrograph, SSC closely follows the waveform of the tides, indicating local deposition and resuspension (Jennings *et al.*, 1997). A consequence of bidirectional flow at Mallard Island and resuspension/ depositional cycles noted here and by Jennings *et al.* (1997), is that there may be net sediment transport upstream during part of the annual, fortnightly, or daily tidal cycles (Tobin *et al.* 1995). The effects of bidirectional flow are taken into account in the estimates of dispersive flux. Although, during the annual cycle, the effects are minimal compared to advective fluxes. On tidal timescales, there is no doubt that dispersive forces play an important role in redistribution of sediments within the Bay-Delta system.

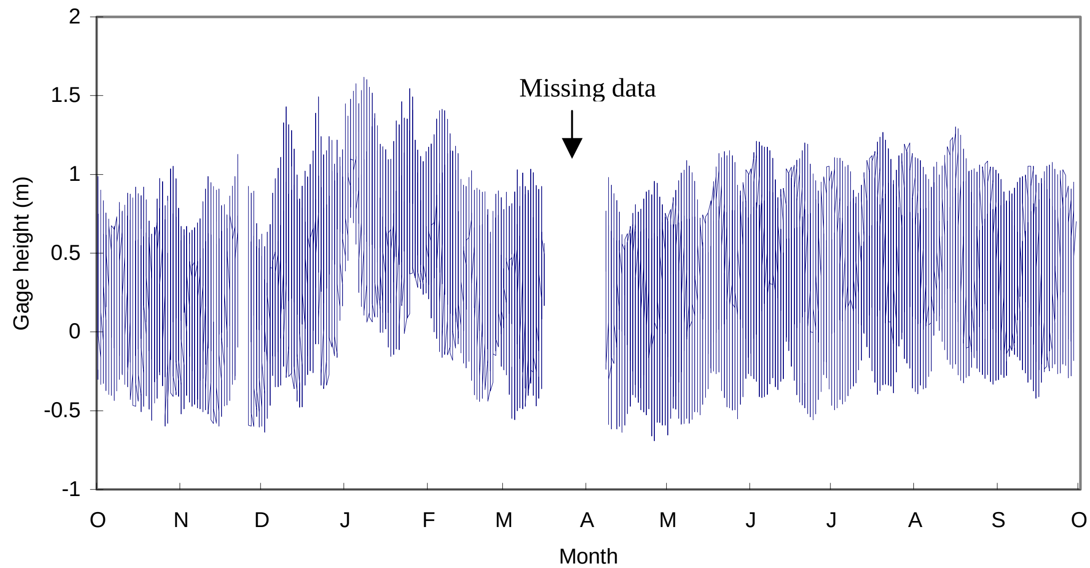

Figure 8. Tide at Mallard Island during the 1997 water year. Data from the California Department of Water Resources (Station ID: MAL).

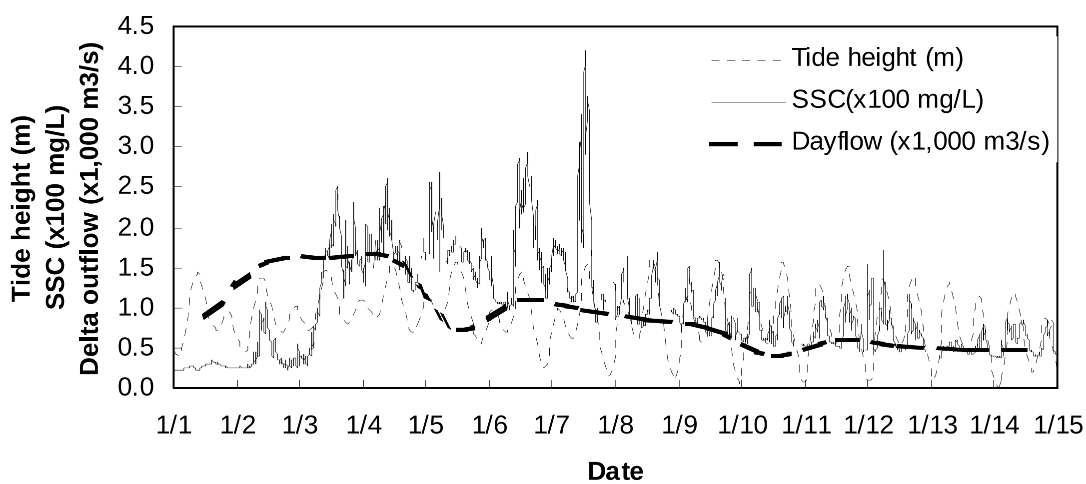

Figure 9. Tide height, Delta outflow, and SSC at Mallard Island during the January 1997 flood.

The direction of the dispersive point-flux mainly is in the opposite direction (landward) of the advective point-flux, at the location of the Mallard Island station. Five explanations can be given for this phenomenon: (1) higher suspended-sediment concentrations in Suisun Bay (seaward end of the study area) as opposed to the lower concentrations in the Sacramento River (landward end) result in a concentration gradient from Suisun Bay to the Lower Sacramento River and, therefore, a net dispersive flux in that direction (landward); (2) the relatively shallow depths in Suisun Bay allow for wind-wave resuspension of bed sediment (Ruhl and Schoellhamer, 1998); (3) flood tide induces a higher bed shear stress than ebb tide (enhancing resuspension and SSC on flood tide), and sediment is more erodible at the beginning of flood tide (Brennan *et al.*, in press); (4) a local turbidity maximum previously has been identified seaward of Mallard Island, which is congruent with explanations 1, 2, and 3 (Schoellhamer, 2001); (5) flood/ebb asymmetry in lateral variability of SSC also is possible.

Trends in suspended-sediment flux

Fluxes calculated here are lesser in magnitude than those calculated by previous authors, though differences in methods may contribute to some variation (Table 2). In addition, some workers included estimates of bed load, however bed load accounts for only about 1.4 percent of the total annual average load (e.g. Porterfield, 1980). Some estimate current bed loads to be about 5 percent of total load (Randal Dinehart, USGS, unpublished data, 2001). In any case, estimates that include the bed load component of fluvial transport still seem to be higher than the estimates for WYs 1995 – 1998. Given that the discharge during the 1995 –1998 period ($45x10^3$ Mm^3) was greater than the average for the last 20 years ($26x10^3$ Mm^3), discharge is not the cause of discrepancies. Intuitively, one would expect flux to be greater, given the drought of the late 1980's and early 1990's that may have caused greater in-channel sediment storage and subsequent mobilization during wetter-than-average years. Krone (1996) suggested a downward trend over time and made a hypothesis that total sediment flux from the Central Valley to the Bay would decrease to 2.1 million yd^3/y (0.85 Mt/y) by the year 2035. Oltmann *et al.* (1999) found a downward trend in sediment flux at Freeport on the Sacramento River from 1960 to 1997, however, the magnitude of the trend was not estimated. If this trend continues, perhaps the predictions of Krone (1996) will be realized. The ramifications of this trend are considered in the following section of this report, which addresses management considerations.

Management considerations and applications

San Francisco Bay sediment budgets

Flux of sediment from the Central Valley previously has been reported to account for approximately 89 – 92 percent of the total input of sediment to the San Francisco Bay sediment budget (Ogden Beeman & Associates, Inc., 1992; Davis *et al.*, 2000). Krone (1979) suggested that the ratio of sediment input to the San Francisco Bay is changing mainly due to reductions in sediment flux from the Central Valley. Krone reported 76 percent of the total flux to the San Francisco Bay was derived from the Central Valley in 1960 and hypothesized that the ratio would reduce to 63 percent in 1990 and 54 percent in 2020, based on increasing water diversions and retention in reservoirs. The present study suggests that the Central Valley supplies about 57 percent of the total flux to the San Francisco Bay if the following assumptions are made:

1. Sediment flux from local watersheds within the nine Bay area counties has not decreased with time, which was asserted by Krone (1979) and is conceptually possible, given increasing population and ongoing conversion of grazing and open space lands to vineyards and urban land uses in the Bay area.
2. The current estimate for sediment flux to the Bay from local tributaries is 0.89 million short tonnes total sediment flux per year (0.83 million short tonnes suspended-sediment flux) (Krone, 1979) equivalent to 0.75 Mt/y [similar to Abu-Saba and Tang, 2000 (0.707 Mt/y)].
3. The estimate calculated in the present study for flux of suspended sediments from the Central Valley during WY 1996 is 1.0 Mt/y.

This is contrary to the conclusion that can be drawn from the work of Davis *et al.* (2000) that used the Simple Model. It is suggested that Davis *et al.* (2000) underestimated sediment discharge from local watersheds by at least a factor of two because the concentration data available for suspended sediment in local watersheds of the nine-county Bay area was low due to data collection during the drought of the late 1980's and early 1990's.

Jaffe *et al.* (1996) and Jaffe *et al.* (2001) demonstrated that San Pablo Bay and Suisun Bay have undergone erosion in shallow areas since the 1950s. For example, from 1942 to 1990, more than two-thirds of Suisun Bay was eroding (Jaffe *et al.*, 2001). The erosion in these bays is likely, in part, a result of reduced sediment supply from the Central Valley (Jaffe *et al.*, 1996), although sediment redistribution within these bays, in response to human and climatic changes during the past 80 – 150 years, also may play a role (James McGrath, Port of Oakland, oral comm., December 2001). A further implication of reducing sediment flux is that sediment dredging requirements in shipping channels may decrease in the future, once sediment stored in the Bay has redistributed and has found a new equilibrium, relative to reduced sediment inputs, changing runoff patterns, changing salinity, and increasing sea level (Dettinger *et al.*, 2001; Knowles, 2001). Reduction in Central Valley sediment flux also implies that sediment derived from local watersheds will become increasingly important as a supply of sediment to the Bay, in general, and in particular to some shipping channels and ports that are affected increasingly by local runoff. There already is evidence that local watersheds are supplying coarse sediment to the Bay, seen as a veneer of sandy sediment on subtidal and intertidal muds near the margins of the southeast Bay and well away from hydraulically active shipping channels (James McGrath, Port of Oakland, oral comm., December 2001), although reworking of older sediment and net erosion could be responsible for this observation.

Resuspension of contaminants stored in bottom sediments

One of the major issues affecting the water quality and biological integrity of the San Francisco Bay is the internal supply of contaminants, such as mercury, from resuspension and biological recycling (Abu-Saba and Tang, 2000). One of the factors influencing the availability of the benthic pool of contaminants is exposure through erosion and redistribution of sediment particles (Jaffe *et al.*, 2001). Erosion apparently is occurring in parts of the Bay where removal through tidal currents and wave action is occurring faster than deposition of new sediment supply from fluvial sources (Jaffe *et al.*, 1996; Jaffe *et al.*, 2001). There still is more than 100 Mm^3 of mercury-contaminated sediment remaining in San Pablo Bay and tens of millions of cubic meters of mercury-laden debris along the margins of Suisun Bay (equivalent to about 10^5 kg Hg) (Jaffe *et al.*, 2001). Bay sediments also contain high concentrations of many other contaminants, which probably include some whose effects are not yet documented. There are a number of mechanisms by which stored contaminants may enter the food web, including physical, chemical, and biological pathways (Davis *et al.*, 1999). The depth of the active sediment mixing layer and the assumption of net deposition or net erosion has strong influences on the outcomes of modeling of contaminant processes in the Bay (Davis, 2002). There are a number of questions still to be answered: What is the depth of the active sediment-mixing layer? How do allochthonous sediment loads determine which layers of sediment get mixed? Will erosion continue to uncover all the contaminants stored in bottom sediments? If not, what is the expected bathymetry of the Bay in the future, given the predicted salinity, freshwater flow volume and timing, sea level, and fluvial sediment flux? Are there differences in bioavailability of contaminants that are recently delivered by allochthonous sediment loads compared to “old” contaminants released from sediments stored within the system?

Sediment supply for restoration projects

Given the decreasing mass of sediment delivered to the Bay from the Central Valley, the implication is that less sediment will be available for restoration of wetlands that require either reuse of dredged material or natural sedimentation through tidal and fluvial supply (Williams, 2001). Furthermore, Williams pointed out that restoration, in itself, also will decrease sediment supply to the Bay as sediment is diverted to wetland areas by deliberate levee breaches and reconnection of the floodplain with the channels. For example, Mount (2001) asserted that “in order to restore lowland rivers in the Central Valley, the winter flood pulses and the smaller, but equally important spring snowmelt pulselets must be able to reach a significant portion of the floodplain” in a way that allows water to move parallel to the stream, thus increasing hydraulic interaction and residence time. Restoring the connectivity of the near-channel floodplain to allow for flow that is parallel to stream channels will undoubtedly capture sediment and related contaminants. Williams (2001) further predicted that a coupling of a decrease in sediment supply and an increase in sea level will result in conversion of some mudflats to shallow subtidal habitats and an increase in shoreline erosion causing losses of fringing marsh and undermining of levees. A ramification of the estimates of upstream flow of sediment associated with tidal advection and dispersion (an average of 0.34 Mt/y) is that this sediment mass may be, in part, available for restoration projects in the Delta.

Concerns have been raised about the adequacy of the regional sediment supply for large-scale tidal marsh restoration (Goals Project, 1999; Williams, 2001), and these concerns are beginning to be addressed. Sediment cores (Byrne et al., 2001), historical maps (Grossinger et al., 1998), and estimates of historical sediment loads (Gilbert, 1917; Kondolf, 2000), when studied together, indicate that marshes depend less on inorganic sediment and more on peat production as they evolve upward through the intertidal zone, and the vast amounts of historical high marsh [there was almost five times as much marshland in the Bay area 200 years ago than exists today (Goals Project, 1999)] was supported by less than one-half the modern sediment supply. It also is expected that the overall demand for sediment to support new marsh restoration can be lessened by starting projects where sediment is abundant and subsidence is moderate, by sizing projects to fit local sediment supplies, and by pacing projects carefully over time (Goals Project, 1999).

Calculation of contaminant flux from the Central Valley

It has been demonstrated that the sediment concentration data collected at Mallard Island by the USGS are suitable for estimating the annual flux of suspended sediments to the San Francisco Bay. Contaminants that attach to sediments persist in the Bay for longer periods than dissolved substances because they tend to accumulate in bottom sediments. The mass of contaminants stored in the sediment may then transfer back into the water column via bioturbation, erosion and resuspension, and diffusion. Contaminant uptake by biota can occur either directly from the sediment or from the water column. A recent study suggested that the Central Valley watersheds are by far the largest pathway for contaminant loads compared to loads from stormwater discharge from local tributaries, treated sewage, atmospheric deposition, and dredge material (Davis *et al.*, 2000), although the bioavailability and contaminant concentrations in some of the latter loads may be higher than in Central Valley sources.

Steding et al. (2000) produced compelling evidence of the influence of the Central Valley on contaminant fate and transport in the Bay using lead isotope data. They found that in 20 years since the phasing out of lead in gasoline began, there has been no reduction in supply of lead from the Central Valley to the Bay. This suggests that flushing of the Central Valley watersheds of traditionally persistent contaminants will continue for some time because the Central Valley sink for lead and other contaminants is so large.

The concern about the supply of sediment-related contaminants from the Central Valley indicates a need for better estimates of loadings for the development of TMDLs. The most relevant application of the present work, with regard to the objectives of the RMP, is the use of SSC data and estimates of sediment flux to improve the understanding of the timing and magnitude of sediment-associated contaminants of concern that enter the Bay from the Central Valley.

Many substances of concern in the Bay can be directly correlated to SSC (Schoellhamer, 1996). For instance, Schoellhamer demonstrated good relations between SSC and total water column chromium, copper, mercury, nickel, lead, and zinc. Continuous SSC data collected at Mallard Island for the WYs 1995 – 1998 offer an opportunity to estimate continuous sediment-associated contaminant concentrations and to derive flux. Unfortunately, the existing data collected in the Delta by the RMP (stations BG20 and BG30) are not sufficient for developing regression models because the routine monitoring by the RMP did not capture the concentration variability associated with floods, when most of the flux of sediment (and therefore sediment-associated contaminants) occurs. Suspended sediment ranged from 5 to 420 mg/L at Mallard Island during WYs 1995 – 1998. However only three of the RMP samples collected at BG20 and BG30 had concentrations of SSC greater than 50 mg/L, the greatest of which was 174 mg/L. About 22 percent of the Mallard Island data collected during WYs 1995 – 1998 had SSC greater than 50 mg/L, and SSC during the six largest flood peaks were greater than 50 mg/L. The greatest average SSC occurring on a single day during WYs 1995 – 1998 was 223 mg/L, a concentration well outside the upper range of the RMP data.

The suspended-sediment sampling station at Mallard Island run by the USGS, which is funded by CALFED until 2004, has used identical sampling equipment and methodologies since 1994. It has been demonstrated that regressions between SSC data and metals that are associated with particles may be used to extrapolate between temporal sampling points, and thus estimate time-continuous concentration data sets (e.g., Schoellhamer, 1996; Whyte and Kirchner, 2000). However, the data collected by the RMP so far is not suitable for this purpose. A methodology has been developed by the USGS to improve the likelihood of capturing the variability of pesticides in the Delta (Jennings *et al.*, 1997). This methodology could be adapted for capturing the variability of all sediment-related contaminants at Mallard Island.

Information Needs

With the management considerations and applications in mind, the following studies are needed to satisfy the aforementioned goals:

Study 1: Continue to use Mallard Island SSC data to estimate sediment flux to the Bay from the Delta and expand data collection to include contaminants of concern using the following steps:

a) Work with DWR to gain an understanding of the errors in magnitude and timing of estimated Delta outflow from the DAYFLOW model. This may include modeling discharge at an hourly time interval to better assess the effects of short time-scale variations in SSC on estimates of loads.

b) Continue to use Mallard Island SSC data to estimate loads on daily, flood, monthly, and annual time steps during subsequent years of data collection to WY 2004. By

2004, there will be 10 years of data that will provide an accurate understanding of intra- and interannual sediment flux dynamics entering San Francisco Bay from the Delta.

c) Consult with scientists from the USGS and others who have specialized knowledge in the collection and analysis of particle-associated contaminants. Determine an appropriate sampling design for gathering data suitable for developing regression equations between OBS measurements at Mallard Island and inorganic and organic particle-associated contaminants of concern.

d) Collect water samples with a focus on flood flow conditions at Mallard Island using the study design determined in Step c and analyze these for sediment particle-associated contaminants including metals, PCBs, PAHs, and historic-use pesticides, as deemed necessary, by the Sources Pathways and Loadings Workgroup of the RMP.

e) In addition, collect water samples or analyze existing data to better determine the variability of suspended sediment in the water column cross section at Mallard Island to adjust the point data collected at the gage on the edge of the channel for water column variability.

f) Develop relations between concentrations of sediment-bound contaminants and OBS.

g) Estimate time-continuous contaminant concentration data for Mallard Island and combine these data with discharge estimates to determine contaminant flux entering the Bay from the Delta.

Study 2: Improve the understanding of the sediment budget and sediment dynamics of the Bay as a predictive tool for future dredging requirements, volume of dredge material available for reuse, and ecosystem change. In addition to the analysis provided in this report, if the currently available SSC and flow data were linked to a hydrodynamic model, the 4-year data set could be extended to predict long-term total sediment delivery for current and future hydrological conditions and estimate sediment availability for restoration projects. This could be done now for planning but should be done in the context of a total of 10 years of data that will be available by 2005.

Study 3: Improve estimates of fluxes of suspended sediments and contaminants from local watersheds within the nine counties of the Bay area.

Study 4: Carry out modeling to determine future estimated bathymetries (e.g., 2005, 2015, 2025, 2050) as a tool for predicting the availability of mercury and other contaminants to the food web. In addition, this kind of analysis will contribute to improving our understanding of shoreline erosion, rates of habitat evolution, and future hydrodynamics.

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