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Estimates of suspended sediment entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California

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Abstract

This study demonstrates the use of suspended-sediment concentration (SSC) data collected at Mallard Island as a means of determining suspended-sediment load entering San Francisco Bay from the Sacramento and San Joaquin River watersheds. Optical backscatter (OBS) data were collected every 15 min during water years (WYs) 1995–2003 and converted to SSC. Daily fluvial advective sediment load was estimated by combining estimated Delta outflow with daily averaged SSC. On days when no data were available, SSC was estimated using linear interpolation. A model was developed to estimate the landward dispersive load using velocity and SSC data collected during WYs 1994 and 1996. The advective and dispersive loads were summed to estimate the total load.

Annual suspended-sediment load at Mallard Island averaged 1.2 ± 0.4 Mt (million metric tonnes). Given that the average water discharge for the 1995–2003 period was greater than the long -term average discharge, it seems likely that the average suspended-sediment load may be less than 1.2 ± 0.4 Mt. Average landward dispersive load was 0.24 Mt/yr, 20% of the total. On average during the wet season, 88% of the annual suspended-sediment load was discharged through the Delta and 43% occurred during the wettest 30-day period. The January 1997 flood transported 1.2 Mt of suspended sediment or about 11% of the total 9-year load (10.9 Mt).

Previous estimates of sediment load at Mallard Island are about a factor of 3 greater because they lacked data downstream from riverine gages and sediment load has decreased. Decreasing suspended-sediment loads may increase erosion in the Bay, help to cause remobilization of buried contaminants, and reduce the supply of sediment for restoration projects.

Keywords: Suspended sediment; Load; Long term; Tide; Interannual; Management implications

1. Introduction

An understanding of suspended sediment supply to the San Francisco Bay system is of paramount importance for the maintenance of a plethora of human and environmental needs and for predicting

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geomorphic evolution under varying future climatic and human perturbations. San Francisco Bay is listed by the State of California as contaminated for mercury (Hg), polychlorinated biphenyls (PCBs) and organochlorine (OC) pesticides in compliance with Section 303(d) of the Clean Water Act. The California Office of Environmental Health Hazard Assessment has issued a health advisory directed at those who consume fish caught in the Bay (OEHHA, 1994, 1997, 1999). Mercury, PCBs and OC pesticides are transported into the Bay attached to suspended sediment particles (e.g. Davis, 2004; Leatherbarrow et al., 2004) and are harmful to aquatic life and humans because of the way the bio-accumulate and bio-magnify in the food chain (Davis et al., 2003). Similar to other coastal areas used for portage (e.g. Eyre et al., 1998), sediment itself constitutes a barrier to local shipping in San Francisco Bay and from 1995 to 2002 an average of 3.1 Mm^3/yr of bottom material was dredged. However, sediment dispersal and deposition during winter storms and reuse of dredged sediment also provide a useful resource for restoring wetland habitats in the Bay-Delta area and there is concern that future climatic and human perturbations may restrict restoration opportunities (e.g. Williams, 2001; Williams and Orr, 2002).

In order to address questions on sediment transport in the Bay and its tributaries, a number of studies have focused on 19th and 20th century sediment loads (Gilbert, 1917; Porterfield, 1980; Goodwin and Denton, 1991; Kondolf, 2000; Wright and Schoellhamer, 2004), tidal and wind-wave driven resuspension (Krone, 1979; Schoellhamer, 1997; Jennings et al., 1997; Ruhl and Schoellhamer, 2004), erosion in various Bay compartments (Jaffe et al., 1998; Capiella et al., 1999; Foxgrover et al., 2004), and sediment budgets for the Bay (Ogden Beeman & Associates, Inc., 1992; Krone, 1996). Several studies have suggested that sediment loads may be decreasing over time (Krone, 1979; Wright and Schoellhamer, 2004) but there has been no recent quantification of the magnitude of current sediment loads entering the Bay, yet many issues important to the Bay Area community such as shipping, recreational and commercial fishing, habitat restoration, human health and environmental water quality are reliant on an understanding of sediment supply. San Francisco Bay is bounded on its upstream end by a large river delta that spans an area of about 3000 km^2 and incorporates thousands of kilometers of waterways and levees. Thus, the upstream boundary of the Bay is tidal and slightly saline. The difficultly in measuring sediment load in a tidal cross-section in which both advective and dispersive forces operate (Schoellhamer and Burau, 1998) and where cycles of deposition and resuspension can occur (Jennings et al., 1997) are some of the reasons for the gap in critical knowledge about recent sediment loads.

In this study, we demonstrate an innovative method for quantification of advective and dispersive loads in a tidal cross-section and make estimates of daily and annual sediment loads entering San Francisco Bay. This information will radically change previous perceptions of the sediment budget for the Bay, provide a valuable tool for estimating trace contaminant loads, and make a further contribution to the state of knowledge about sediment transport from large river basins to active continental margins.

2. Materials and methods

2.1. Physical description

Mallard Island (Fig. 1) was chosen as the location for study because it represents the upper end member of San Francisco Bay and because it is the location of long term monitoring by the California Department of Water Resources (DWR) (station code MAL). The channel adjacent to Mallard Island conveys runoff from 154,000 km^2 [$>37\%$ of the land area of California (411,000 km^2)]. The channel depth at the Mallard Island gage is approximately 7.6 m, while the adjacent shipping channel has a maximum depth of about 17 m, the total channel width is approximately 940 m and the location has an average tidal range (DWR unpublished data) of 1.25 m (mean lower low water to mean higher high water). Tides at Mallard Island are mixed semi-diurnal (Fig. 2). Mallard Island is approximately 8 km downstream of the confluence of the Sacramento and San Joaquin Rivers. Upstream from the sampling location, the channel broadens in to a complex system of sloughs, modified channels, and reclaimed islands many of which are productive farming lands that together make up the Sacramento-San Joaquin River Delta. Freshwater

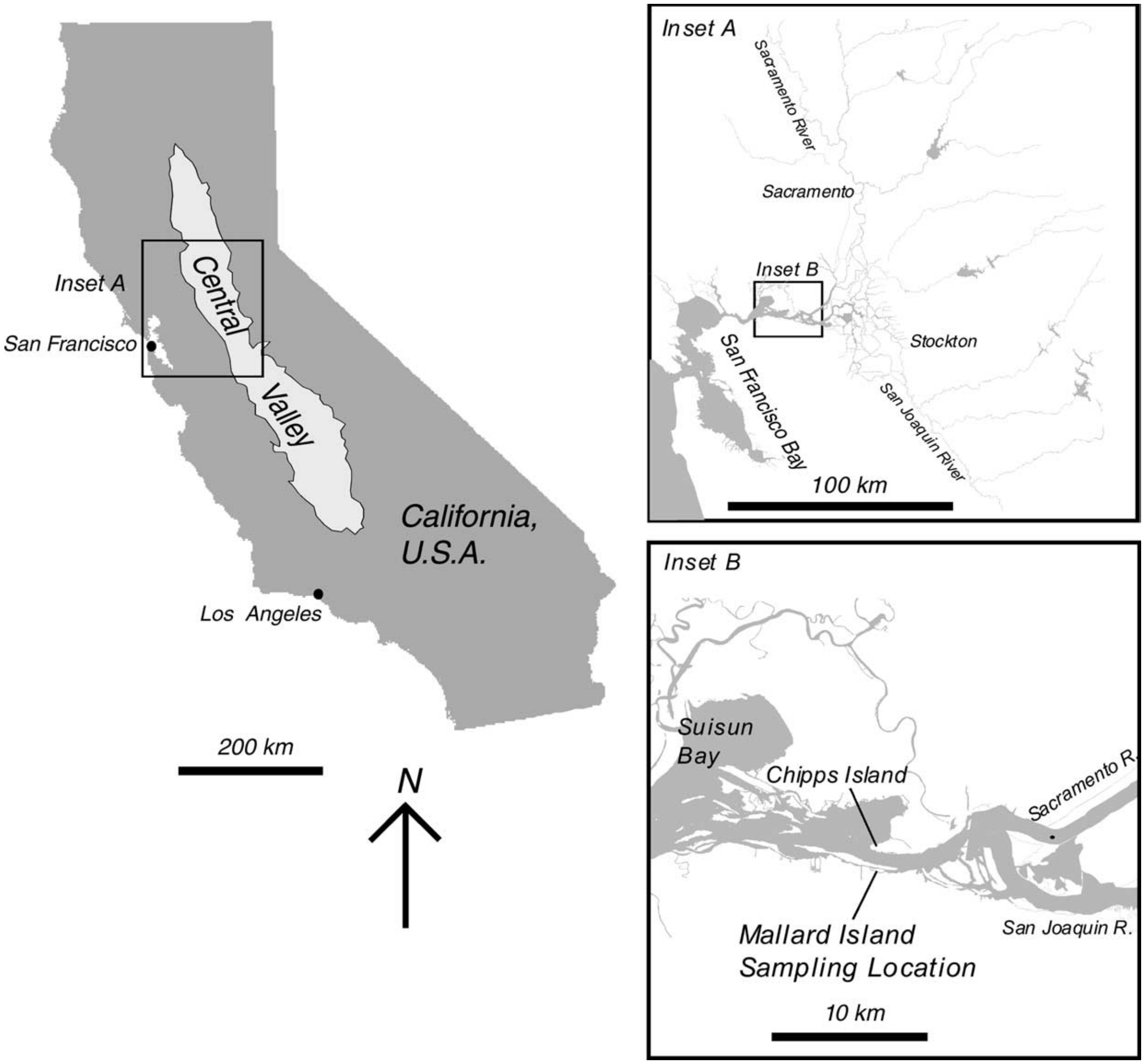

Fig. 1. The Mallard Island sampling location.

is removed from the Delta channels to satisfy demand for drinking water and irrigation both within and outside the Delta. There are two deepwater channels that connect the city of Stockton on the San Joaquin River and state capital of Sacramento on the Sacramento River to the Bay for shipping purposes. In addition, during high flows, floodwaters are diverted north of Sacramento though the Yolo Bypass. Discharge at Mallard Island is influenced by numerous reservoirs further upstream that are managed for flood control, water supply, and environmental flows. This manipulated plumbing system is the conduit for water and sediment between the Sierra Nevada, Central Valley, and San Francisco Bay.

2.2. Suspended-sediment data

Suspended sediment concentration (SSC) data were collected at Mallard Island from February 9, 1994, to September 30, 2003 (3521 days) (Buchanan

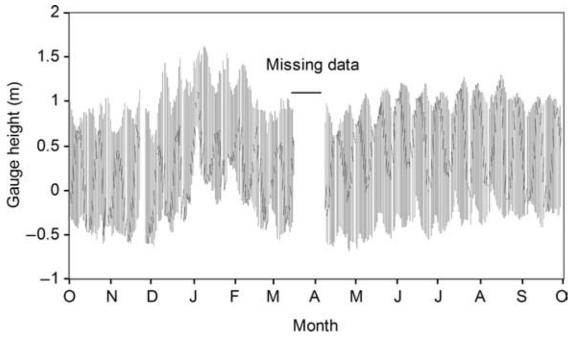

Fig. 2. Tide at Mallard Island during the 1997 water year. Data from the California Department of Water Resources (Station ID: MAL).

and Schoellhamer, 1996, 1998, 1999; Buchanan and Ruhl, 2000, 2001; Buchanan and Ganju, 2002–2005). Data were collected every 15 min, giving as many as 96 data points per day. 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 but these were not analyzed in detail primarily because the surface data are more complete. As a result of equipment malfunction, biological fouling, and vandalism, 900 days, or 26% of the potential days on record, retained no data even at the upper sensor. There has been critical discussion on the differences between 'suspended-sediment concentrations (SSC)' or 'total suspended solid concentrations (TSS)' (Gray et al., 2000). The collection of water samples, the analysis of sediment in suspension SSC, and use of the term 'SSC' in this report conforms to the methods outlined in Buchanan and Ruhl (2000).

2.3. Hydrology

Given that water circulation at the Mallard Island site is tidally influenced, the net (tidally averaged) discharge cannot be gauged 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, 2004a) 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. The degree of accuracy of DAYFLOW output is affected by the DAYFLOW computational scheme and the accuracy and limitations of the input data. The input data include the principal Delta stream inflows, Delta precipitation, Delta exports for irrigation and drinking water, in-Delta drinking water and irrigation demand, and irrigation return flows. Both monitored and estimated values are included as described in this DAYFLOW program documentation (Interagency Ecological Program, 2004a). Currently, all calculations are performed using data for the same day. Because of the large size of the watershed, a flood hydrograph might take 7–14 days to rise and fall. Despite the simple water balance structure of the model, the model does account for storm effects and therefore adequately provides data for loads calculations.

DAYFLOW data are available for 1956 to the present from the Interagency Ecological Program (IEP) (Interagency Ecological Program, 2004b). Delta outflow estimated using the DAYFLOW Model is the longest-running record of water discharge entering San Francisco Bay from the Delta. This data is periodically updated when model parameters are refined by new information. Data used in this report are from the last data update that was published on January 7, 2004. Tidal gage height data have been measured at Mallard Island since 1987 and are available from the DWR.

2.4. Load calculation

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

$$\begin{aligned}[L] =& [[A]][U_a][C_a] + [[A]][U'_a C'_a] \\ &+ [A' U'_a][C_a] + [A' C'_a][U_a] + [A' U'_a C'_a] \\ &+ [[A]]([U_{dt}][C_{dt}])_a + [[A]]([U_{dv}][C_{dv}])_a \\ &+ [[A]]([U'_t C'_t])_a + [[A]]([U'_v C'_v])_a \\ &+ [A'(U'_t C'_t)_a] + [A'(U'_v C'_v)_a],\end{aligned} \quad (1)$$

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 types of forcing on the total load. In their respective order, they are: (1) the load contribution of river discharge (advective load), (2) correlation between fluctuations of velocity and concentration (dispersive load), (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).

2.4.1. Simplifications and assumptions

Limitations of the data collected at Mallard Island preclude solving all terms in the load 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 load) is the only term that can be estimated over the desired timescale in this study, though simplification of that term also is required. However there was sufficient data to estimate a dispersive flux correction (discussed in detail below).

2.4.2. Advective load

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

$$\text{Daily advective load} = C_{av}Q_{DO} \quad (2)$$

where C_{av} is the average SSC for a 24-h period and Q_{DO} is the Delta outflow 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 load of suspended sediment in metric tonnes (t). On days with no SSC data, load was estimated by linear interpolation. SSC was estimated by interpolating across the data gaps, and the load was estimated by multiplying the estimated SSC by daily discharge. Interpolation of the SSC data was preferred to interpolating between load measurements because the estimate retained the variation associated with discharge.

The advective load method assumes that the point SSC data at Mallard Island is representative of the entire cross-section. Although lateral and vertical structure of the concentration profile is almost unknown, it is reasonable to assume that during high-flow (when most of the sediment is delivered), the cross-section at Mallard Island is well mixed due to high velocities. During low-flow, this may not be the case, due to stratification effects, flood/ebb asymmetries, and other phenomena. The data collected 2 m above the bed was used to make an estimate of cross-section SSC variation which was then used in the estimation of errors in loads estimates (details to follow in the section on errors).

2.4.3. Other load terms

Estimating the total residual load at Mallard Island as the product of daily DAYFLOW discharge and mean concentration neglects several terms from the total load equation. The magnitude of the first four terms of the load equation can be estimated via point data at the Mallard Island site. This method estimates the bias produced when the advective load estimate alone is used to compute total load, 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. We estimate these neglected terms in our error calculation.

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

$$[l] = [[u][c]] + [u'c'] + [[u]c'] + [u'[c]] \quad (3)$$

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

Three sets of SSC and velocity data were available for this analysis; one from WY 1996 (near-surface), and two from WY 1994 (near-surface and mid-depth). An Acoustic Doppler current profiler (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 load was calculated using the bin closest to the elevation of the optical sensor used to measure SSC. Here we calculate point-load rather than cross-sectionally averaged load, which is valid for comparing advective and dispersive load.

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 load cannot be compared between the deployments.

For illustrative purposes, cumulative frequencies of flow during WY 1996 were used to identify high, average, and low-flow periods. Flows above the 90% cumulative frequency (2747 m^3/s) were considered high, flows at 50% (396 m^3/s) were considered average, and flows below 10% (226 m^3/s) were considered low.

2.5. Combining advective and dispersive load estimates

To correct the positive bias associated with calculating WYs 1995–2003 advective load alone, an equation was fit to the scatter of points created by plotting Delta outflow versus the ratio of dispersive to advective load for the available data (Fig. 3). At infinitely high flows, the advective load would be wholly responsible for transport, while at zero flow, the advective load should go to zero, resulting in a dispersive/ advective load ratio of plus or minus infinity. The dispersive load is rarely in the same direction as the advective load at Mallard Island (points greater than zero).

2.6. 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-h record, the SSC data were filtered using a low-pass filter with a cutoff period of 30 h. The record then was integrated daily, and divided by 96 (number of readings per day) to get a filtered, daily-integrated

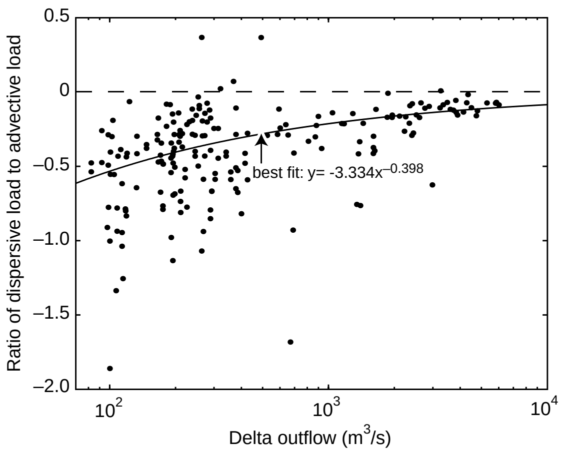

Fig. 3. Ratio of dispersive-to-advective point-loads versus Delta outflow, for all three data periods (198 points). A negative ratio indicates opposing directions of dispersive and advective point-loads. The RMS error value is 0.29 (in the units of the ratio, i.e. dimensionless). Note that the error is mainly due to the large scatter at low flows, which are much less important in the overall watershed sediment advection. At flows above 530 m^3/s (visual cutoff), the RMS error is reduced to 0.14.

average concentration (cf_{ave}). The mean daily concentrations from the same record (C_{ave}) were used to calculate the % difference between the filtered average and the daily geometric average [$(cf_{ave} - C_{ave})/cf_{ave}$]. The square root was taken of the sum of the squares of all the % differences to give a rms error of 0.67% (error A in the formula below). Such a small error reflects that fact that there were few outliers in the data.

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 partially empty and fill the Delta (Oltmann, 1998), an error of at least ±5% is likely (error B in the formula below). The error associated with laboratory analysis of SSC was set at ±5% (Gray et al., 2000) (error C in the formula below). The estimated error associated with the regression between OBS and SSC was ±10% [see regressions in Buchanan and Schoellhamer (1996, 1998, 1999), Buchanan and Ruhl (2000, 2001) and Buchanan and Ganju (2002, 2003)] (error D in the formula below).

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, 2001; Buchanan and Ganju, 2002; 2003) have not been included in this analysis of load (reasons explained previously). 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%). During WY's 1996, 1997, 1998, 1999, 2000, and 2001, the % differences between the upper and lower sensors were +27, +11, +2, +10, +30, +27 (Buchanan and Schoellhamer, 1998, 1999; Buchanan and Ruhl, 2000, 2001; Buchanan and Ganju, 2002, 2003). In years when the near-bottom concentrations are greater than the near-surface concentrations, a negative bias in load 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 (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 on average about 15%. Further, if it is assumed that lateral variations are similar to the vertical, then the total error associated with water column variation will be closer to ±30% (error E in the formula below). Cross-sectional sampling at similar suspended-sediment monitoring stations in the Delta indicates that the typical cross-sectional variability is 25% (Wright and Schoellhamer, 2005), so a 30% error appears realistic. The errors (shown in Table 2) were calculated as follows and applied to all nine water years:

$$\begin{aligned}\text{Error} &= (A^2 + B^2 + C^2 + D^2 + E^2)^{0.5} \\ &= (0.67^2 + 5^2 + 5^2 + 10^2 + 30^2)^{0.5} \\ &= \pm 32 \text{ percent}\end{aligned}$$

3. Results

3.1. Delta outflow for water years 1995–2003

DAYFLOW estimates followed an intraannual cycle typical of Californian Mediterranean (dry summer subtropical) climate, where the majority of flow occurs during the wet season (Fig. 4). The wet season during WY 1995 to WY 2003 started in December and ended 3–6 months later (February, March, April or May) depending on seasonal rainfall and snowmelt. For consistency, however, the wet season of each water year was considered December 1 to May 31. On average (WYs 1995–2003), 83% of the Delta outflow occurred during the wet season and 34% occurred during the wettest 30-day period

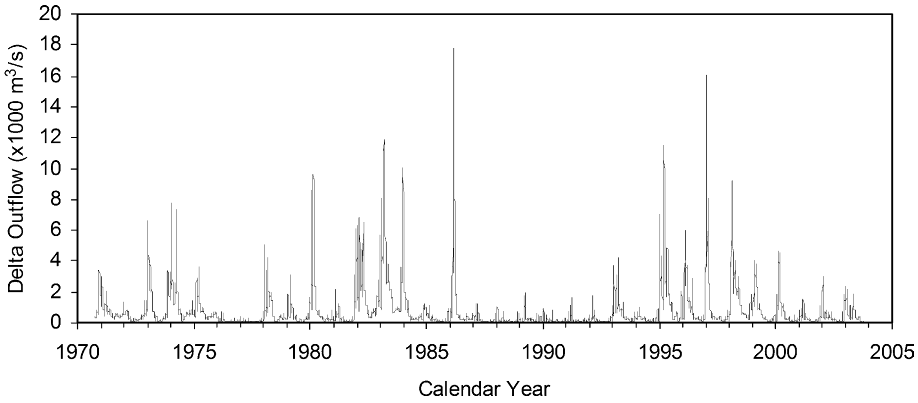

Fig. 4. Daily water discharge (Delta outflow) at Mallard Island using output from the Department of Water Resources DAYFLOW model.

of each year. Discharge varied interannually from 8.6×10^3 Mm^3 in WY 2001 to 53.6×10^3 Mm^3 in WY 1998. This interannual variation does not fully reflect the long-term variability of the system. Discharge during WYs 1971–2000 varied from 3.1×10^3 to 79.3×10^3 Mm^3 (26 times) with a coefficient of variation (CV) of 0.76 (note that the period 1971–2000 was chosen to be consistent with the published United States National Oceanic and Atmospheric Administration [NOAA] National Climate Data Center [NCDC] climatic averages. Mean annual discharge for WYs 1995–2003 was greater than average (29.6×10^3 Mm^3 compared to 24.9×10^3 Mm^3 for WYs 1971–2000). Of interest, average annual discharge was only 8.5×10^3 Mm^3 during the 8 years previous to our study period (WYs 1987–1994). This appears to have decreased the net transport of sediment during those years and increased the amount of storage in the watershed and channels that subsequently could be eroded or resuspended during later years when rainfall, snow melt, and runoff were greater. This is evidenced by greater daily average SSCs during the 1995 flood compared to the 1997 flood despite greater discharge during 1997 and lower daily average SSCs during the 1996 and 1998 floods compared to the floods of 2000 and 2002 despite much lower discharge during the 2000 and 2002 floods. An alternative explanation for the interannual variation in SSC is that there is a constant but finite amount of erodible material. Increasing flow increases the amount of mobilized material up to a point where there is no more material to be mobilized. Then SSC decreases as flow increases via dilution. Further observation of the system after a future break in drought may corroborate one or other of our hypothesis of episodic storage and release.

3.2. SSC and daily suspended-sediment load at Mallard Island

Daily average SSC at Mallard Island was highly variable, ranging from 14 to 223 mg/L. The highest instantaneous concentrations reached 420 mg/L on January 7th 1997 during the largest flood of the study period, approximately 4 days after the peak in Delta outflow. Instantaneous SSC can be greater or less than the daily average SSC mainly because of the influences of tide on deposition and resuspension (Jennings et al., 1997). For example, during the January 1997 flood, SSC on the day of maximum discharge varied from 27 to 250 mg/L and show a waveform similar to the tidal waveform. A full description of the SSC variation has been reported for each year (Buchanan and Schoellhamer, 1996, 1998, 1999; Buchanan and Ruhl, 2000, 2001; Buchanan and Ganju, 2002–2005). As predicted, advective load of suspended sediment at Mallard Island reflected the intraannual cycle of water discharge. Dispersive point-load (load estimated from point measurements and assumed to be representative of the entire water column) was calculated for the period for which data were available (Fig. 5, December 17 1995–March 5, 1996, near-surface, high Delta outflow). During high flows, the advective point-load dominates (Fig. 5), which is expected because the large volumes of water moving

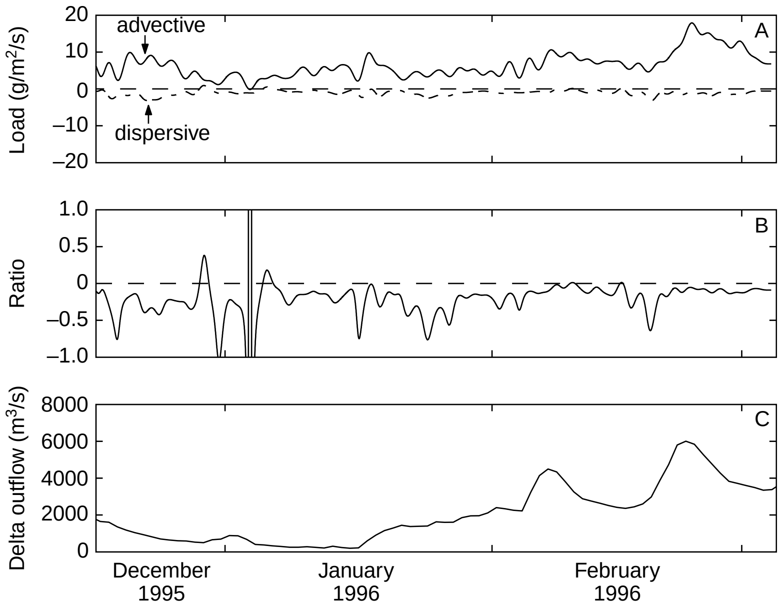

Fig. 5. Advective and dispersive point-loads at Mallard Island (A), ratio of dispersive-to-advective point-load (B), and Delta outflow (C), December 17 1995–March 5 1996.

seaward through the river are responsible for the transport of sediment. Dispersive point-load magnitude averages about 11% of the advective point-load magnitude during this above-average flow period (mean discharge = 2,116 m^3/s). The direction of the dispersive point-load mainly is in the opposite direction (landward) of the advective point-load 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-load magnitude near surface averages about 49% of the advective point-load magnitude, and almost always is in the opposite direction (landward) (Fig. 6). For the same period, the mid-depth dispersive point-load averages 52% of the advective point-load. Thus, for lower flows, dispersive load is relatively more important in estimating total load. This result is similar to a scaling analysis of the relative magnitudes of the advective and dispersive load, which calculates the two loads to be on the same order of magnitude for low flows (David Schoellhamer, USGS, unpublished data, 2001).

These results demonstrate that load is overestimated at this location when only the advective term is considered, and the overestimate is largest during low-flow periods. However, the advective load will be strongly dependent on flow, suggesting that at lower flows the overestimate of a small load might not be as important to an estimate of the total annual sediment load from the Delta to the Bay. Fig. 7 presents the three data sets, displaying the load that would be estimated by using only the advective term, and the total load. The ADCP deployments were in different locations, so the load cannot be compared directly between the WY 1994 and 1996 deployments.

Average dispersive point-load for a given discharge was estimated using the curve shown in Fig. 3. On an annual basis, tidal dispersive load 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, 0.40 Mt during WY 1998, 0.23 Mt during WY 1999, 0.17 Mt during WY 2000, 0.12 Mt during WY 2001, 0.12 Mt during WY 2002, and 0.16 Mt during WY 2003. Thus, if tidal effects had not been taken into account, sediment load from the Central Valley to the Bay would have been over estimated by an average of 0.24 Mt per year or about 20% of the total 9-year load.

Dispersive loads for each discharge then were added to the advective loads to give the best estimate of suspended-sediment load per day. While the use of

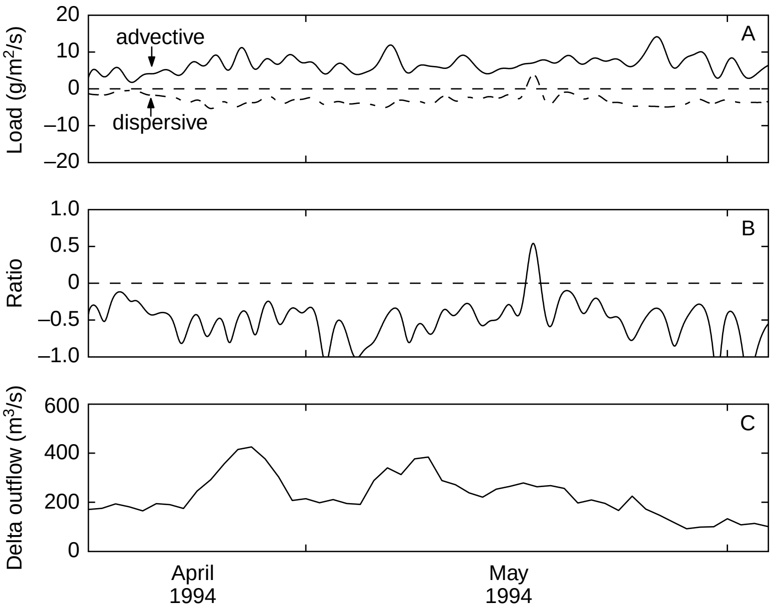

Fig. 6. Advective and dispersive point-loads at Mallard Island (A), ratio of dispersive-to-advective point-load (B), and Delta outflow (C), April 15 1994–June 4 1994.

point-load data to estimate a bias in average cross-sectional load may not be optimal, the analysis here shows that the dispersive load must be considered even during high-flow periods. On average (WYs 1995–2003), 88% of the annual load (dispersive and advective) was discharged through the Delta during the wet season of a water year, 43% was discharged during the wettest 30-day period, 19% was discharged during the wettest 7-day period, and 3.7% of the suspended-sediment load occurred on the wettest 1-day period (Table 1). The largest flood during WYs 1995–2003 occurred in January 1997. This flood alone transported 1.2 Mt of suspended sediment or about 11% of the total accumulated load for the 9 years (10.9 Mt). When the second peak in January 1997 was included, 1.7 Mt of suspended sediment were transported, or about 15% of the 9-year total load.

Annual suspended-sediment load at Mallard Island varied from 0.26 ± 0.08 Mt in WY 2001 to 2.6 ± 0.8 Mt in WY 1995 and averaged 1.2 ± 0.4 Mt (Table 2). Given that the water discharge for the 1995–2003 period was greater than the average discharge, it seems likely that the average sediment load may be less than 1.2 ± 0.4 Mt. Water year 1996 had an average discharge and, therefore, the WY 1996 suspended-sediment load (1.0 ± 0.3 Mt) may be our best hypothesis of the average annual suspended-sediment load entering the Bay from the Central Valley. 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. If the assumption is made that the SSC data and loads presented here are representative of the variability over a wider range of flow conditions, a regression between load and flow (Fig. 8) can be used to estimate long term loads. Using the annual Delta outflow for WY 1971–2000, an average long term sediment load of 1.0 ± 0.3 Mt is determined (similar to WY 1996 in spite of non-linearity of the equation on Fig. 8). Regardless of how one chooses to manipulate the data, it is clear that the new loads estimates presented here are less by a factor of about 3 than those previously calculated (Table 2). This will be discussed below.

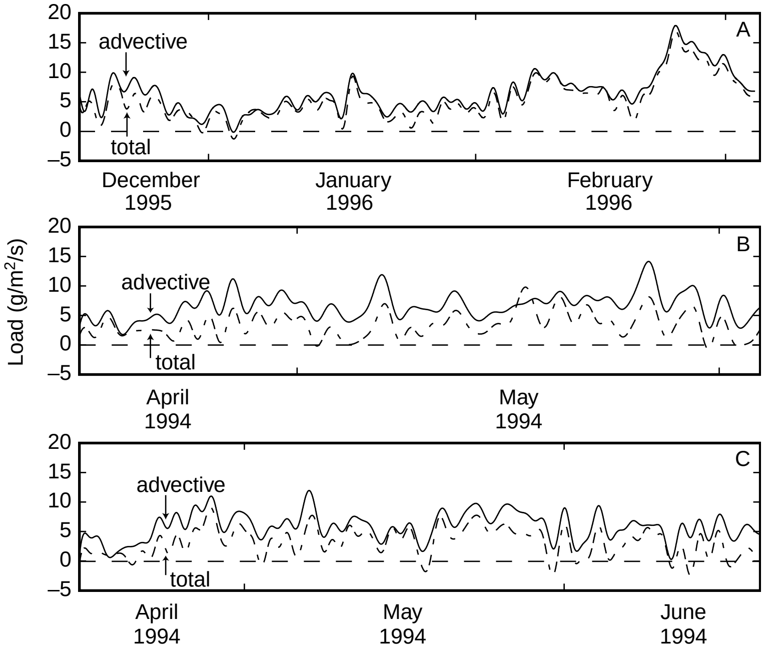

Fig. 7. Comparison of advective and total point-loads at Mallard Island. December 17 1995–March 5 1996, near surface (A), April 15 1994–June 4 1994, near surface (B), and April 15 1994–June 20 1994, mid-depth (C).

4. Discussion

4.1. Suspended-sediment concentration and flow-data quality

Approximately 26% of the days between February 9 1994, and September 30 2003, had no data recorded. It happened that the majority of the missing data occurred during low-flow periods, thus 86% of the load was measured, and only 14% 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% in addition to the other errors) in the estimate of the load for the 1998 water year, it certainly had little effect on the overall estimate of the average load for the 9-year period.

In most studies of suspended-sediment load, the discharge of water is measured on a smaller time interval than concentration. Thus, the scientific literature concerning measuring and estimating riverine load is rich with methods that interpolate between concentration data points (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 min (96 data points per day), and thus a potential loss in accuracy

Table 1
Intra-annual variation of the sum of advective and dispersive suspended-sediment load at Mallard Island for water years 1995–2003 (for example, during water year 1995, 22% of the total annual suspended-sediment load was transported during seven consecutive days)

Water year	1-day (%)	7-day (%)	30-day (%)	Wet Season December 1 to May 31 (%)
1995	6.1	22	38	92
1996	2.5	13	36	88
1997	9.6	44	70	96
1998	2.7	17	45	84
1999	1.6	9	31	81
2000	2.5	16	49	89
2001	3.2	18	41	86
2002	3.1	18	44	86
2003	2.0	11	37	88
Average	3.7	19	43	88

Table 2
Annual suspended-sediment load at Mallard Island calculated for water years 1995–2003

Author	Data calculation period	Annual suspended-sediment load (Mt/y)
This study	1994/1995	2.6±0.8
This study	1995/1996	1.0±0.3
This study	1996/1997	2.2 ± 0.7
This study	1997/1998	2.4±0.8
This study	1998/1999	0.84±0.27
This study	1999/2000	0.66±0.21
This study	2000/2001	0.26±0.08
This study	2001/2002	0.31±0.10
This study	2002/2003	0.55±0.17
This study	9-year average	1.2±0.4
Krone (1979)	Average for 1960	3.0
Smith (1963)	?	3.3[a]
Schultz (1965)	?	4.5[a]
U.S.A.C.E (1967)	?	4.0[a]
Porterfield (1980)	1909–66	4.1
Ogden Beeman & Associates (1992)	1955–90	2.4

Previous estimates are included for comparison.
[a] These estimates include bed-sediment load and suspended-sediment load from local tributaries to San Francisco Bay as well as load from the Central Valley.

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 load at Mallard Island, but the loss of precision is perhaps random.

The use of the daily time step is satisfactory to estimate load. 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 (35–45 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 with no adjustment for varying discharge lag 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 could be done if future applications warrant this level of effort.

4.2. Dispersive load

The direction of the dispersive point-load mainly is in the opposite direction (landward) of the advective point-load, 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 load in that direction (landward); (2) the relatively shallow depths in Suisun Bay allow for wind-wave resuspension of bed sediment (Ruhl and Schoellhamer, 2004); (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., 2002); (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. A consequence of bidirectional flow and a seaward gradient of increasing SSC at Mallard

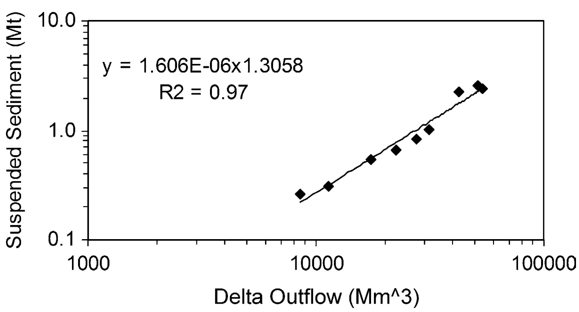

Fig. 8. The relationship between annual Delta outflow and annual suspended sediment load at Mallard Island (WY 1995–2003).

Island is that there may be net sediment transport upstream during part of the annual, fortnightly, or daily tidal cycles (Tobin et al., 1995). Our estimated dispersive load accounts for this upstream transport and for the 9-year study period, the landward dispersive load was 20% of the seaward advective load. This has implications for the future estimation of contaminant loads. For example, if concentrations of contaminants such as mercury on resuspended particles downstream from Mallard Island are greater than those upstream, there would be a greater percentage of dispersive load for mercury relative to suspended sediments.

4.3. Trends in suspended-sediment load

Loads calculated here are lesser in magnitude than those calculated by previous authors (Table 2), though differences in methods undoubtedly contribute to some variation (for details on the method of each previous author see Krone, 1979; Smith, 1963; Schultz, 1965; U.S.A.C.E., 1967; Porterfield, 1980; Ogden Beeman & Associates, 1992). In addition, some workers included estimates of bed load, however bed load accounts for only about 1.4% of the total annual average load (Porterfield, 1980). Estimates that include the bed load component of fluvial transport still seem to be higher than the estimates for WYs 1995–2003. Given that the discharge during the 1995–2003 period ($29.6\times 10^3\ Mm^3$) was greater than the average for the last 30 years ($24.9\times 10^3\ Mm^3$), discharge is not the cause of discrepancies.

The most recent of the previous estimates (Ogden Beeman & Associates, 1992) estimated suspended sediment loads by use of a rating curve for sediment load versus water discharge using sediment data gathered at Freeport on the Sacramento River and Vernalis on the San Joaquin River. Because no sediment data were available from the tidal channels of the Delta, the rating curve was applied to Delta outflow to estimate load into the Bay. In doing so, Ogden Beeman & Associates (1992) assumed that the relation between water discharge and SSC did not vary in time, no deposition occurred in the Delta, and water exports remove sediment from the Delta. Wright and Schoellhamer (2004), however, show that the water discharge and SSC relation in the Sacramento River has changed with time. Wright and Schoellhamer (in press) used Mallard Island sediment loads reported here and estimates of sediment load into the Delta to determine that two-thirds of the sediment that enters the Delta deposits there which results in a deposition rate similar to measurements by Reed (2002), and $116{,}000\ m^3$ of sediment deposited in the forebay used by the water export projects from 1999 to 2004 (Scott Woodland, California Department of Water Resources, writ. comm., 2005). The loads presented here for WY 1995–2003 are not subject to these issues.

Krone (1996) suggested a downward trend over time and made a hypothesis that total sediment load from the Central Valley to the Bay would decrease to 2.1 million cubic yards per year (0.85 Mt/y) by the year 2035. Wright and Schoellhamer (2004) found that the sediment yield of the lower Sacramento River has decreased by about one-half from 1957 to 2001. If this trend continues, perhaps the predictions of Krone (1996) will be realized. The ramifications of this trend are considered in the following sections, that addresses management considerations.

5. Management considerations and applications

5.1. San Francisco Bay sediment budgets

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

1. Sediment load 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 of long term average for sediment load entering the Bay from local tributaries 0.83 million short tonnes suspended-sediment (Krone, 1979) equivalent to 0.75 Mt/y.
3. The estimate calculated in the present study for long term load of suspended sediments from the Central Valley is 1.0 Mt/y.

San Pablo Bay and Suisun Bay have undergone erosion in shallow areas since the 1950s (Jaffe et al., 1998, 2001; Capiella et al., 1999). For example, from 1942 to 1990, more than two-thirds of Suisun Bay was eroding (Capiella et al., 1999). 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. A further implication of reducing sediment load 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). Dredging figures for the period 1955–1990 (4.5 Mm^3/yr) versus figures for the period 1995–2002 (3.1 Mm^3/yr) indicate that this may already be occurring. Reduction in Central Valley sediment load 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.

5.2. 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 (Johnson and Looker, 2003). 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, 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. The depth of the active sediment mixing layer and the assumption of net deposition or net erosion strongly influence the outcomes of modeling of contaminant processes in the Bay (Davis, 2004).

5.3. 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. Shellenbarger et al. (2004) found that restoring tides to former commercial salt ponds in South San Francisco Bay may greatly reduce sediment deposition elsewhere. 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 0.24 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. Marsh accretion tracks sea level rise with a combination of peat production and inorganic sedimentation. Peat production dominates when sea level rise is slow. 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 around San Francisco Bay depended less on inorganic sediment and more on peat production as they evolved upward through the intertidal zone. 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, at a given time, the 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).

5.4. Calculation of contaminant load 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 load of suspended sediments to the San Francisco Bay from the Central Valley. 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 large. Several recently released mercury reports describing current knowledge and data needs for management of the Bay also highlighted the need for continuing evaluation of contaminant loads entering the Bay from the Central Valley (Johnson and Looker, 2003; Hetzel, 2004). Many substances of concern in the Bay can be directly correlated to SSC (Schoellhamer, 1997; Whyte and Kirchner, 2000; Leatherbarrow et al., 2004). Future studies will likely use the SSC data and estimates of sediment load presented here to improve the understanding of the timing and magnitude of sediment-associated contaminants of current management concern (mercury, PCBs, and organochlorine pesticides) that enter the Bay from the Central Valley.

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