

# **Sources and Impacts of Sediment Inputs into the Water Column of San Francisco Bay**

A Report for the San Francisco Bay Subtidal Goals Project (Dec. 2008)

Prepared for the California Coastal Conservancy, National Oceanic and Atmospheric Administration, San Francisco Bay Conservation and Development Commission, and Association of Bay Area Governments

Andrew N. Cohen, San Francisco Estuary Institute, Oakland, CA

This paper discusses sediment budgets and assessments of sediment inputs to San Francisco Bay; the impacts of increased turbidity and sedimentation on organisms; and some potential effects of changing sediment inputs. Dredging, the disposal of dredged materials, and in-Bay mining activities are discussed in terms of their effect on sediment budgets (by removing sediment from the Bay) and their injection of sediment into the water column. Except for the material that is injected into the water column during the disposal process (forming temporary sediment plumes), the deposit of dredged materials on the bottom at disposal sites in the Bay is addressed under the Stressor "Deposit Sediments or Shell." The direct effects on habitats and organisms of removing sediment (changing bottom topography, entraining and removing organisms, etc.) are addressed under the Stressor "Remove or Disturb Sediments, Shell or Bedrock." The injection of contaminants or nutrients into the water column by these activities, and the importing, exporting, deposition, bioavailability and impacts of sediment-associated contaminants or nutrients are addressed under the Stressors "Change Contaminant Inputs" and "Change Nutrient Inputs."

## **Overview**

Over the years, there have been a substantial number of studies in San Francisco Bay that have estimated sediment inputs and outflows, estimated erosion and sedimentation rates and associated changes in Bay bathymetry, and in some cases organized these data into sediment budgets. The estimates were made by a variety of methods and usually have substantial uncertainties associated with them, making it difficult to compare the results of different studies, and to assess the extent to which changes in the results among studies over time reflect true temporal trends rather than methodological differences. Nevertheless, the overall results point to an initial large increase in sediment inputs to the Bay from the Sacramento-San Joaquin river systems in the last half of the 19th century, followed by a long-term, continuing decline, with concomitant changes in sedimentation and erosion patterns in the Bay. The most recent studies of changes in the Bay's bathymetry indicate that there has been net erosion of the Bay since around the 1950s (Jaffe et al. 1998; Cappiella et al. 1999; Foxgrover et al. 2004; Fregoso et al. 2008), though previous analysis showed net deposition during this period (Krone 1996; see Figures 5 and 6 below).

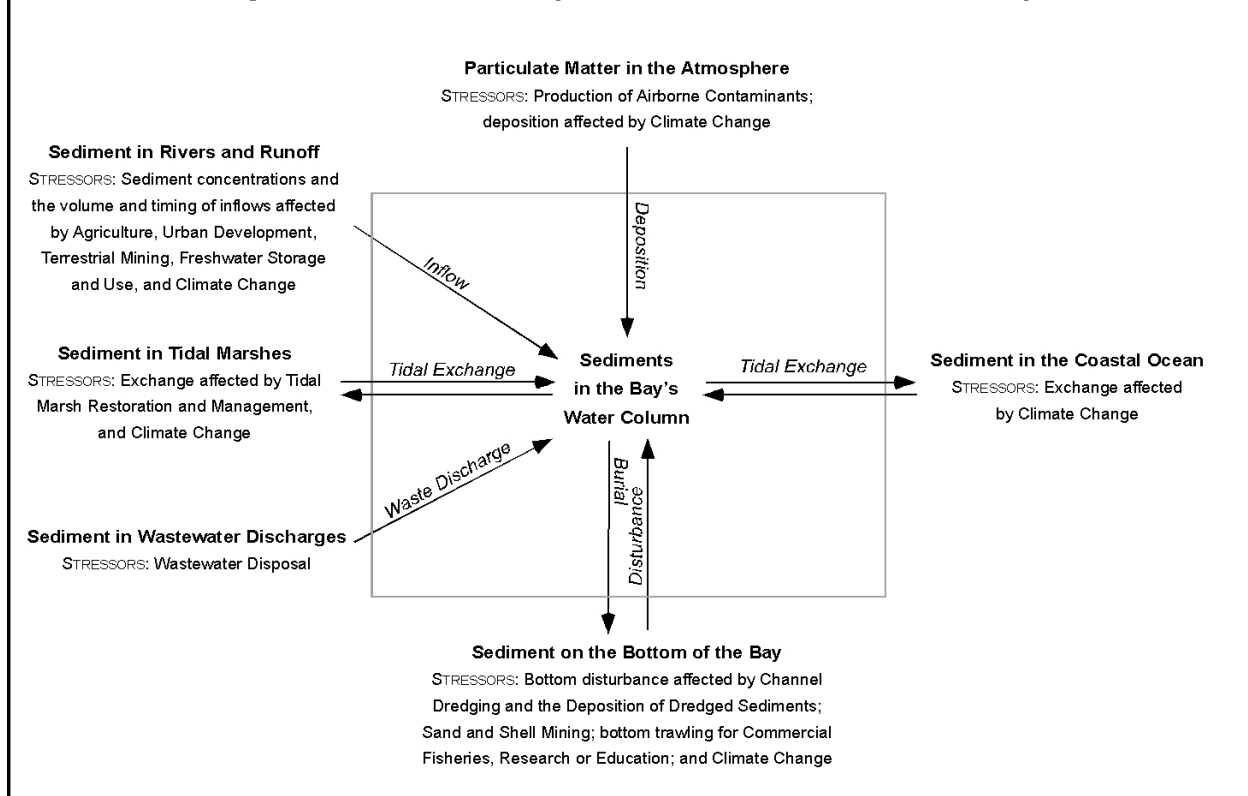
Numerous studies have documented the potential for impacts on organisms from increases in sediment concentrations in the water column, aside from any effects of sediment-associated contaminants. These impacts include clogging or damaging the gills of fish and invertebrates, especially filter feeders; repelling or attracting adult fish and changing their behavior; providing cover for prey species, and reducing predation rates of predatory species; and reducing light penetration, photosynthesis and the productivity and growth of eelgrass, seaweeds and phytoplankton (ABP Research 1999; Levine-Fricke 2004). These effects become evident only at high sediment concentrations, so the assessment of activities that inject sediment into the water column pivots on the question of whether the sediment concentrations are raised high enough, for long enough, over a large enough area to be a significant concern.

Increased inputs of sediment from external sources promotes higher deposition rates, shoaling, marsh accretion, more rapid burial of contaminants and nutrients, and an increased need for channel dredging. Conversely, reductions in sediment inputs promote the erosion of sediments, loss of shoal areas, marsh retreat, exposure and release into the water column of buried contaminants and nutrients, and a reduced need for channel dredging.

### **Sediment Pathways and Budgets**

Sediments from various sources can be carried into the Bay with freshwater inflows in rivers or runoff, or enter the Bay directly in minor amounts as sediment in wastewater discharges or as particulate matter deposited from the atmosphere. Relative to riverine inputs, wastewater discharges and atmospheric deposition are insignificant as overall sources of sediment entering the Bay (though sediment in wastewater may be locally significant in the areas adjacent to outfalls), and are not treated further in this paper. Sediment settled on the bottom can be resuspended by currents or wind waves or by human activities that disturb the bottom. Tidal waters moving between the Bay and the ocean and between the Bay and its tidal marshes can carry sediment in or out of the Bay (Fig. 1).

**Figure 1. Sediment Pathways and Stressors in San Francisco Bay**



Sediment budgets are constructed to better understand the flows of sediment into and out of an ecosystem and the accumulation or loss of sediment from a system (Schoellhamer et al. 2005). Studies that have contributed to our understanding of San Francisco Bay's sediment budget have typically taken the Bay and its bottom as the "system." Storage in the system is usually estimated by examining changes in the Bay's bathymetry between the beginning and end of a period, calculating the amount of sediment that would need to have been added or removed to make the changes, and dividing by the length of the period to yield an annual rate of accumulation or loss. Sediment inflows are usually estimated from data on water flows and sediment concentrations in tributary rivers. The net flux of sediment in or out of the Golden Gate is usually calculated as inflows minus anthropogenic outflows (i.e. sediment removed from the Bay by mining or dredging) minus change in storage.

### San Francisco Bay Sediment Budgets

While investigating the impact of hydraulic mining debris, Gilbert (1917) constructed a sediment budget to assess the fate of material washed out of the Sierra Nevada region by mining and other activities including farming, grazing and road construction, over the period from 1849 to 1914 (Table 1). The "system" for this budget was not the Bay itself, but included both the Bay and those parts of its tributary rivers and watershed where quantities of mining debris and other sediments were deposited. The number that Gilbert used for sediment input to this system was an estimate of the volume of soil and debris washed from the lands that are tributary to the Delta. He began with prior estimates of the hydraulic mining debris produced in several parts of

the Sierra Nevada. These had been made by multiplying the amount of water used to wash away the overburden, measured in miner's inches, by a "duty", the approximate amount of material removed per miner's inch. The duty varied greatly depending on "the quantity of water used, the pressure, the character of the material washed, and the grade and size of the sluices," with a reported range between 1 and 28 cubic meters of debris per inch, producing estimates of substantial uncertainty. Gilbert checked these by surveying the excavations that were left behind by mining activities at various sites in the Yuba River watershed, imagining what the original slopes had been prior to mining, surveys whose aggregate accuracy Gilbert estimated at  $\pm 10\%$ . The estimate he produced by this method was 51% larger than the earlier estimates based on water usage made at the same sites. He then adjusted upward the corresponding estimates made over larger areas of the Sierra Nevada, extrapolated these to areas where estimates had not been made, and added estimates for other, non-hydraulic types of mining

**Table 1. Sediment Budget for 1849-1914 from Gilbert 1917**

Source (+) or Fate (-) of Sediments	$10^6 \text{ m}^3$	$10^6 \text{ m}^3/\text{yr}$	Method of Estimation
Wasted from the land surface tributary to Suisun Bay	1,816	27.5	Volume of mining debris calculated from amount of water used in hydraulic mining and surveys of mining excavations, along with estimates of erosion from agriculture, roads and trails, overgrazing and the natural degradation of the land surface.
Deposited in the Sierra Nevada, the piedmont or the channels of valley rivers	-677	-10.3	Estimated from surveys of deposits and various extrapolations.
Deposited in the Bay	-876	-13.3	Estimated from changes in bathymetry between USC&GS charts.
Outflow to the ocean	-38	-0.6	Estimated "arbitrarily".
Deposited on "inundated lands" consisting of Central Valley flood basins and Bay and Delta marshes	-225	-3.4	Remainder of above.

(placer mining, quartz mining and drifting), and ended up with an overall estimate of mining debris that was "nearly eight times as great as the volume moved in making the Panama Canal."

To this estimate Gilbert added what were possibly rougher estimates for loss of soil from farming (multiplying estimates of farm area by 2 inches lost for active farms and 4 inches lost for abandoned farms), from road and trail construction (multiplying the total length of mapped public roads by an average width of 10 feet and a loss of one foot of depth with 85% of this reaching the streams, and adding allotments for unmapped and private roads, abandoned roads, and trails), from overgrazing and from natural erosion, which altogether added nearly 42% to his mining debris estimate. From this total he subtracted estimates of the volume of debris lodged in mining dumps, in canyons and in and along stream and river courses in the mountains and in the piedmont lands immediately below them, and in the beds of the Sacramento, Feather and San Joaquin Rivers in the Central Valley, estimates made as above by a combination of measurements, extrapolations and educated guesses, which totaled 37% of the sediment input. He made no direct estimate of the amount of sediment captured in the lateral flood basins of the Central Valley rivers or in the Delta marshes, which "would be difficult to measure" (leaving these quantities to be included in the balance of the budget equation, the deposits on "inundated lands"), and so nowhere does he actually provide an estimate of the amount of sediment entering the Bay through the Delta. Nor does he estimate or include in his budget the sediment contributed by the local creeks and rivers draining into San Francisco Bay.

Gilbert estimated the volume of sediment deposited in the Bay by comparing the water depths on successive charts produced by the U.S. Coast and Geodetic Survey (USC&GS), which spanned periods of 20 to 41 years in different parts of the Bay, and extrapolating the results to the 66-year period of his analysis. The total amounted to 48% of the sediment input. He made no mention of correcting for sea level rise, noted significant inaccuracies in the methods of the earliest surveys and raised questions about the plane of reference used, and noted that the precision of the surveys was generally inadequate for calculating changes of contour in irregular channels, where he instead made rough guesses. While his overall approach to determining changes in sediment deposition was similar to that used in later studies, the specific methods of analysis and the precision of surveys have improved.

Gilbert's estimate of the amount of sediment carried out through the Golden Gate was, as he stated, "necessarily arbitrary," based largely on the observation that "the outflowing stream is distinguished from the water it invades by a yellowish tinge." This estimate accounted for just over 2% of the sediment input. Subtracting the sediment deposited in the mountains, along and in the rivers and in the Bay, and sediment carried out to sea, from his estimate of the debris produced by mining and the soil washed from the land, resulted in a quantity that Gilbert called deposits on inundated lands, including in these the Central Valley flood basins and the Bay and Delta marshes. These account for the remaining 12% of the sediment input.

Unlike later sediment budgets for the Bay, Gilbert estimated sediment inputs as the volume of mining debris and sediment washed from the land, rather than as an estimate based on the concentration and mass of sediment carried by the rivers. Thus he was able to make all of his initial measurements and estimates in volume units with no need to convert between mass of sediment and the volume of sediment deposits (which is a critical step in the budgets discussed below). However, he made no mention of and no correction for the differing densities of different types of deposits. This could be a significant oversight because, for example, the rock and dirt that occupied a cubic meter of space before it was excavated or water-blasted from a hillside, may occupy a significantly larger volume when it is deposited in a mining dump, lodged in a canyon, or accumulated in a river bed or on the bottom of the Bay, and these different types of deposited material may themselves differ considerably in the amount of sediment material contained in a given volume due to variations in particle size and shape, entrained organic material, degree of compaction, etc. For example, if a given amount of material occupied on average 50% more volume when deposited in the watershed or Bay than it did when it was part of the original undisturbed sediment and rock, then the 1,816 million cubic meters of sediment input in Gilbert's budget would have produced 2,720 million cubic meters of deposited sediment, and the deposits on inundated lands, calculated as the remainder from the budget, would have been 1,159 rather than 225 million cubic meters, the latter then being in error by 81%.

Smith (1965) did not explicitly construct a sediment budget, but provided most of the estimates needed to assemble a rough one for the Estuary (Bay plus Delta) or the Bay (Table 2). Estimates of sediment inputs were derived from measurements of suspended sediment concentrations in tributary waters over a relatively short period (1957-59). These were used to determine the relationships between water discharge and sediment discharge in different water courses,<sup>1</sup> which were then used to estimate sediment discharge over a longer period (1909-1959) using long-term estimates of water discharge. In this case, the water flows were modified by assuming 1960 levels of water withdrawals, so it's really an estimate for 1960 water system

---

<sup>1</sup> For example, the sediment discharge-water discharge relationship determined for the Sacramento River is shown in graph form in Smith's (1965) Fig. 4.

conditions with water inputs assumed to be those of the preceding 50 years. Suspended sediment estimates were then adjusted to include bed load, estimated by a combination of measurements and modeling. This work was conducted by Porterfield et al. (1961; see also Porterfield 1980), producing estimates of the average annual mass of sediments carried into the Bay and Delta by their tributary rivers.

**Table 2. Partial San Francisco Estuary Sediment Budget from data in Smith 1965**

Source (+) or Fate (-) of Sediments	10 <sup>6</sup> MT/yr	10 <sup>6</sup> m <sup>3</sup> /yr	Method of Estimation
Inflow to Delta	4.57	5.38	Based on Porterfield et al.'s (1961) suspended sediment measurements of 1957-59 and estimates of total sediment, adjusted to 1909-59 water flows with 1960-level withdrawals. Converted to a volume of Bay and Delta sediment deposits by assuming a bulk dry density of 0.801 MT/m <sup>3</sup> for suspended load and 1.44 MT/m <sup>3</sup> for bed load.
Inflow to Bay from local rivers	0.76	0.91	As above.
Removed with Delta water withdrawals	-0.20	-0.23	Assumes water withdrawals at 1960 levels of 4,500 cfs, carrying suspended sediment only.
Deposited in the Delta		-1.2	Assumes average maintenance dredging equals 85% of deposition, the minor sloughs not being dredged.
Deposited in the Bay		-4.6	Based on calculations of bathymetric change from comparisons of successive USC&GS charts, extrapolated to the 1855-1956 period

Smith converted these mass estimates into volume estimates by assuming a bulk dry density when deposited of 0.801 MT/m<sup>3</sup> (=50 lb/ft<sup>3</sup>) for suspended load and 1.44 MT/m<sup>3</sup> (=90 lb/ft<sup>3</sup>) for bed load. (The appropriateness of these conversion factors will be discussed below with those used by other studies.) He estimated the amount of sediment removed from the Delta in water withdrawals based on the relative volume of water withdrawn, and the amount of sediment deposited in the Delta based on maintenance dredging records. Subtracting these from his estimated input to the Delta of 5.4 million cubic meters/year, yields an estimated input to the Bay from the Delta of 3.9 million cubic meters/year; adding the input from local rivers produces an overall estimate of sediment input to the Bay of 4.8 million cubic meters/year.

Like Gilbert (1917), Smith estimated the size of deposits in the Bay by comparing the charts produced by a series of bathymetric surveys conducted in different parts of the Bay, determining the average rates of sediment deposition or erosion between surveys, and extrapolating to a common time period for the entire Bay. His resulting estimate, an average rate of deposition of 4.6 million cubic meters/year from 1855 to 1956, is close to his estimate of sediment inputs to the Bay, suggesting that the summed losses from the Bay (e.g. from sand mining, ocean export, and net deposition on tidal marshes) should be small. However, several cautions are in order. Since the large sediment inputs and presumably large sediment deposits of the hydraulic mining era occurred during the early part of the 1855-1956 period, the rate of sediment deposition in the later part of this period — corresponding to Smith's sediment input estimates based on 1960 water system conditions and 1909-59 water flows — should be significantly below the average rate. On the other hand, though Smith considered USGS data on ground subsidence in Santa Clara County and found the impact on sediment deposition rates to be minor and not worth including in his estimates, he apparently did not consider the impact of sea level rise, which could significantly raise the estimates. In addition, the several other sources of uncertainty in these estimates should be kept in mind.

Krone (1979) described a generally similar sediment budget for the Bay (Table 3), though some of the quantities were incorrectly shown in the illustration at the end of his paper, which led to erroneous citings of these quantities by later authors (including himself).<sup>2</sup> Like Smith (1965), Krone used Porterfield et al.'s (1961) mass estimates of suspended sediment loads from local rivers derived from 1957-59 suspended sediment concentration measurements, but did not adjust them to a longer period of water discharge data. To estimate suspended sediment inputs into the Delta and from the Delta into the Bay, Krone used a longer period of suspended sediment concentration measurements (1957-65) and a later 50-year period of water flows (1921-71) than Smith (1965). To estimate total sediment loads he added bed load equal to 0.065 of the total load by weight. He then converted these to volume estimates by assuming a bulk dry density when deposited of 0.529 MT/m<sup>3</sup> (=33 lb/ft<sup>3</sup>).

**Table 3. San Francisco Bay Sediment Budget for 1960 from Krone 1979**

Source (+) or Fate (-) of Sediments	10 <sup>6</sup> MT/yr	10 <sup>6</sup> m <sup>3</sup> /yr	Method of Estimation
Inflow to Bay from Delta	3.25	6.1	Estimated from the relationship of measured suspended sediment to river discharge for 1957-65, and 1921-71 water flows adjusted to 1960 water system facilities and withdrawals, with bed load assumed to be 0.065 of the total load. Converted to a volume of Bay sediment deposits by assuming a bulk dry density of 0.529 MT/m <sup>3</sup> .
Inflow to Bay from local rivers	1.0	1.9	Based on Porterfield et al.'s (1961) suspended sediment measurements of 1957-59, not adjusted to a longer flow period, with bed load and volume conversion as above.
Upland disposal of dredge sediments		-0.76	Not stated.
Deposited in the Bay		-3.5	Based on interpolations to 1923-50 of Smith's (1965) calculations of bathymetric change based on USC&GS charts, corrected for sea level rise.
Outflow to the ocean		-3.75	Remainder of above.

Krone's (1979) sediment budget figure shows annual land disposal of about 750,000 cubic meters of dredged sediments, with in-Bay disposal (which doesn't affect the sediment budget) being seven times that; the source of these numbers is not explained, but they are presumably derived from dredging records. Deposition rates for 1923-1950 are extrapolated from Smith's (1965) calculations based on USC&GS charts, and adjusted for sea level rise of 2 millimeters per year, as measured over the long-term (1860-1970) at the Golden Gate. Net sediment lost to the ocean was calculated as the balance after upland disposal and Bay deposition were subtracted from the sediment inputs.

Ogden Beeman Associates, working with Ray Krone, produced a sediment budget for the period 1955-1990 for the Long Term Management Strategy (LTMS) project (Ogden Beeman 1992) (Table 4). Estimates of the sediment input to the Delta from the Central Valley were based on sediment concentration measurements made on the Sacramento and San Joaquin rivers for periods between 1957 and 1988, adjusted to Delta inflows for the 1955-1990 period.

<sup>2</sup> Krone's (1979) Figure 6 shows the average annual sediment deposition in the Bay as "New Annual Deposit 5.5 M", where M = million cubic yards. However, the figure leaves out annual sediment erosion from the South Bay of 0.91 million cubic yards, for a net annual deposit of ≈4.6 million cubic yards (≈3.5 million cubic meters). The figure also confusingly reports "4.0 M net outflow to ocean plus 0.9 M from erosion of So. SF. Bay," when the "net outflow to ocean" is actually 4.9 million cubic yards (≈3.7 million cubic meters). This was apparently sufficient to confuse later authors, including Krone himself, who in 1996 summarized the earlier paper as finding "a total of...about 5.5 Mcy accumulated in the bays, and 4.0 Mcy exited the Golden Gate" annually.

Sediment input from the Delta to the Bay was then estimated by assuming that there was no deposition within the Delta, and that the sediment inflow was apportioned between Delta withdrawals and Delta outflows according to the size of these flows. Sediment input to the Bay from local rivers was taken from Porterfield's (1980) estimate of average sediment inflows for 1909-1966. Porterfield (1980) used suspended sediment concentrations measured during 1957-1967 and adjusted to water flows for 1909-1966, plus various models to calculate bed load. As did Krone (1979), Ogden Beeman converted the sediment mass estimates for both Delta and local inputs to volume estimates by assuming a bulk dry density when deposited of 0.529 MT/m<sup>3</sup> (=33 lb/ft<sup>3</sup>).

**Table 4. San Francisco Bay Sediment Budget for 1955-1990 from Ogden Beeman 1992**

Source (+) or Fate (-) of Sediments	10 <sup>6</sup> MT/yr	10 <sup>6</sup> m <sup>3</sup> /yr	Method of Estimation
Inflow to Bay from Delta	2.4	4.5	Estimated from the relationship between river discharge and daily measurements of suspended sediment at Sacramento (1957-66 and 1980-88) and Vernalis (1957-88), and river and Delta outflow records for 1955-90, assuming no deposition in the Delta (and ignoring bed load?). Converted to volume by assuming a bulk dry density of 0.529 MT/m <sup>3</sup> .
Inflow to Bay from local rivers	0.81	1.5	Based on Porterfield's (1980) estimate of sediment production for 1909-66, with volume conversion as above.
Upland disposal of dredge sediments		-0.31	Based on dredging records.
Deposited in the Bay		-3.1	Based on National Ocean Service bathymetric surveys conducted around 1955 and 1990, corrected for South Bay subsidence and sea level rise.
Outflow to the ocean		-2.6	Remainder of above.

Ogden Beeman compiled dredging records from the U.S. Army Corps of Engineers and the U.S. Navy, and calculated the average rate of dredging during 1955-1990 at 4.5 million cubic meters/year, with upland disposal of about 300,000 cubic meters/year. Estimates of sediment deposition in the Bay were based on National Ocean Service (NOS, formerly the U.S. Coast and Geodetic Survey) charts, with corrections for sea level (estimated at 50 mm (0.16 feet) of rise over the 35-year period)<sup>3</sup> and for subsidence in the southern part of the South Bay.<sup>4</sup> Ogden Beeman, arguing that the Bay's tidal marshes are probably not accumulating sediment fast enough to keep up with sea level rise, estimated an upper bound on the amount of sediment deposited in these marshes of 130,000 cubic meters/year, which they considered too small to be worth including in the sediment budget.<sup>5</sup> As in Krone (1979), sediment lost to the ocean was calculated as the balance after dredge disposal on land and sediment deposition were subtracted from the sediment inflows.

Schoellhamer et al. (2005) constructed a different sediment budget for 1955-1990, and produced two budgets for the 1995-2002 period, one using all the years' data and one that deleted two years with very high water flows to produce a "normal water year" estimate for the

<sup>3</sup> This is in fact the change in chart datums between the 1955 and 1990 charts, which were based on two different tidal epochs. The actual measured sea level rise at the Golden Gate from 1955-1990 was nearly 100 millimeters (0.32 feet). The correction is significant; applied over the area of the Bay it amounts to a change of 0.55 million cubic meters/year, or about 18% of the sediment deposition estimated in this study.

<sup>4</sup> The subsidence correction is also significant, amounting to 0.71 million cubic meters/year, or about 23% of the sediment deposition estimated in this study.

<sup>5</sup> This estimate was based on sea level rise over the 35-year period of 0.16 feet, but elsewhere (Appendix F) they note that the actual measured rise over this period was 0.32 feet.



period (Table 5). Sediment inflow to the Bay was estimated from new measurements of suspended sediment concentrations and estimates of suspended sediment loads for 1995-2003 made at Mallard Island at the head of the Bay (McKee et al. 2002, 2006), and adjusted for Delta outflows for the relevant periods. Bed load was not included in these estimates because it was small in previous budgets (D. Schoellhamer pers. comm.). Sediment input from local rivers was based on Porterfield's (1980) estimate of total sediment loads for 1909-1966.

**Table 5. San Francisco Bay Sediment Budgets for 1955-1990, 1995-2002, and 1995-2002 normal water years, from Schoellhamer et al. 2005**

Source (+) or Fate (-) of Sediments	10 <sup>6</sup> MT/yr			Method of Estimation
	1955-1990	1995-2002	1995-2002 normal WY	
Inflow to Bay from Delta	1.1	1.3	0.8	Estimated from the relationship between river discharge and suspended sediment measurements at Mallard Island in 1995-2003, and Delta outflow records for 1955-90.
Inflow to Bay from local rivers	0.81	1.5	0.9	Based on Porterfield's (1980) estimate of sediment production for 1909-66.
Eroded from the Bay bottom	1.4	1.8	2.4	For 1955-90, extrapolated from USGS and Ogden Beeman analyses of bathymetric changes, and converted to mass by assuming a bulk dry density of 0.529 MT/m <sup>3</sup> (D. Schoellhamer pers. comm.). For 1995-2002, based on a model of sediment movement.
Inflow of sand from ocean	2.9	2.9	2.9	Derived from the change in bathymetry in the Central Bay plus the quantity removed by sand mining. Mass conversion probably as above.
Upland disposal of dredge sediments	-0.1	-1.3	-1.0	Based on USACE and US Navy dredging records.
Sand mining	-0.88	-1.8	-1.8	Estimated from Hanson et al. 2004.
Deposited in tidal marshes	-0.19	-0.19	-0.2	Estimated by assuming marshes have maintained their elevations relative to sea level rise.
Suspended sediment outflow to the ocean	-5.0	-4.2	-4.0	Remainder of above.

Estimates of changes in sediment storage in the Bay for the 1955-1990 budget were taken from Ogden Beeman (1992) for the Central Bay, and based on recent re-analyses by USGS scientists of the USC&GS and NOS charts for the rest of the Bay (Suisun Bay: Cappiella et al. 1999; San Pablo Bay: Jaffe et al. 1998; South Bay: Foxgrover et al. 2004). There are no bathymetry charts that are recent enough to allow an estimate of the change in sediment storage in the Bay between 1995 and 2002. Instead Schoellhamer et al. (2005) used a salinity model of the Bay that had been modified to incorporate sediment transport, deposition and erosion (Lionberger 2003). Schoellhamer et al. argued that there is a large flow of sand from the ocean into the Bay along the bottom of the Golden Gate. They estimated this inflow as the sediment accumulated landward of the Golden Gate as revealed by the analysis of bathymetric change in the Central Bay (Ogden Beeman 1992), plus the quantity removed by sand mining. Dredge sediments disposed on land and sediments removed by sand mining were estimated from available records. Sediment deposited on tidal marshes was estimated by assuming that the rate of accumulation was sufficient to keep pace with sea level rise, estimated at 2.17 millimeters per year. Sediment export to the ocean was calculated as inflows (from the Delta and local rivers, and sand from the ocean) minus other outflows (upland dredge disposal, sand mining, net export to marshes) plus change in storage. This calculation was done in mass units,

so quantities initially estimated as volumes — the change in sediment storage in the Bay, the influx of ocean sand at the Golden Gate, the sediment deposited on tidal marshes, and possibly the material removed by upland dredge disposal and sand mining — were converted to mass units using a sediment density figure of 0.529 MT/m<sup>3</sup> (D. Schoellhamer pers. comm.).

There are some striking differences between the two sediment budgets constructed for 1955-1990 (Tables 4 and 5). Schoellhamer et al. (2005) estimated annual sediment inflow from the Delta at 1.1 million metric tons, which is less than half of Ogden Beeman's (1992) estimate of 2.4 million metric tons. The general approach used was similar: establish the relationship between sediment concentrations and water flows by measuring suspended sediment concentrations over a short period, and use this to estimate sediment flows based on water flow data over a longer period. The period and locations for the sediment concentration measurements differed between the two studies so some difference may be expected, but the size of the difference is surprising. The main reason for this difference may be that Ogden Beeman assumed that there was no sediment deposition in the Delta, while Schoellhamer et al. (2005) relied on Wright and Schoellhamer's (2005) finding that about two-thirds of the sediment entering the Delta is deposited there (D. Schoellhamer pers. comm.). Other large differences — in the change in stored sediment and in sediment exported to the ocean — are partly explained by Schoellhamer et al.'s treatment of ocean-derived sand that accumulated in the Central Bay as a distinct category rather than as a change in stored sediment.

### **The Role of Sediment Density**

All studies since the 1960s have estimated sediment inflows to the Bay based on measurements of suspended sediment concentrations in the rivers, with the inflows calculated initially on a mass basis; and have estimated sedimentation or erosion in the subtidal Bay and deposition in tidal marshes based on changes in bathymetry and surface level, which are calculated initially on a volume basis. Constructing a sediment budget thus requires conversion from one of these units to the other. A change in the volume of bottom sediment has three components, sediment derived from outside the system, organic material derived from within the Bay or marsh (that is, material derived from phytoplankton, benthic algae, eelgrass or marsh plants), and pore space that is filled with water or air depending on the sediment's position relative to the tide. The desired conversion factor relates the mass of the externally-derived sediment to the volume it and its associated pore space would occupy if there were no organic material derived from within the Bay or marsh. At least in non-marsh sediments, the amount of organic matter is usually small and can be ignored, so the conversion factor is approximately the dry bulk density of *in situ* sediment.

Table 6 shows densities that have been used as volume-to-mass conversion factors for sediment in different San Francisco Bay studies; and Table 7 shows dry bulk densities that have been measured or estimated for Bay sediments. The values reported for Bay sediments range from 0.400-1.409 MT/m<sup>3</sup>, while the values used in Bay studies as conversion factors range from 0.529 to 0.852 MT/m<sup>3</sup>. The use of one or another conversion factor can lead to wildly different values derived from the same data and analysis. For example, Ogden Beeman (1992) estimated the average annual sediment flow from the Delta into Suisun Bay in 1950-1990 to be 2.62 million tons (=2.4 million MT), and used a conversion factor of 33 lb/ft<sup>3</sup> (=0.529 MT/m<sup>3</sup>) to report this in volume terms as 5.88 million yd<sup>3</sup> (Ogden Beeman 1992, Table 5) (=4.5 million m<sup>3</sup>). However, Jaffe et al. (2007) used a conversion factor of 0.85 MT/m<sup>3</sup> to report Ogden Beeman's estimate in volume terms as 2.79 million m<sup>3</sup>, which is less than 2/3 of the volume that Ogden Beeman had reported. Used in a volume-based comparison of sediment flows or in a sediment

budget, these two numbers — 4.5 million m<sup>3</sup> and 2.8 million m<sup>3</sup> — which are essentially different translations of a single analysis of sediment flow, would produce very different results.

**Table 6. Densities used for Volume-to-Mass Conversion**

Purpose	lb/ft <sup>3</sup>	MT/m <sup>3</sup>	Source
For a sediment budget	33	0.529	Krone 1979, Ogden Beeman 1992
To compare estimates of sediment flow	33	0.529	McKee et al. 2002, 2006
To compare potential sediment accumulation to sea level rise	33	0.529	Van Geen & Luoma 1999
For model calibration	33	0.529	Ganju et al. 2008
For marsh soils in a sediment budget	35	0.561	Ogden Beeman 1992
For suspended load in sediment budget	50	0.801	Porterfield et al. 1961
To convert and compare sediment flows	52.3	0.852	Porterfield 1980, Jaffe et al. 2007
For bed load in a sediment budget	90	1.443	Porterfield et al. 1961

**Table 7. Dry Bulk Densities Reported for Bay Sediments**

Material	lb/ft <sup>3</sup>	MT/m <sup>3</sup>	Source
<i>in situ</i> SF Bay bottom sediment	25-50	0.400-0.801	Ogden Beeman 1992
bottom sediment in San Pablo Bay	31	0.496	Smith 1965] reporting USACE analysis of dredge spoil samples
mineral portion of South SF Bay marsh soils	35	0.561	Ogden Beeman 1992 citing Krone 1987, using Pestrong 1972's data
bottom sediment in South Bay	45	0.721	Smith 1965] reporting USACE analysis of dredge spoil samples
sediment delivered within the Bay	45.05	0.722	Smith 1965 <sup>a</sup> based on model
area-weighted mean of Bay bottom sediment	47.42	0.759	Based on Smith 1965] data
sediment delivered to the Bay/Delta system	48.84	0.782	Smith 1965 <sup>a</sup> based on model
sediment delivered to the Bay/Delta system	49-50	0.785-0.801	Smith 1965] reporting USGS and DWR estimates based on model
bottom sediment in Central Bay	49	0.785	Smith 1965] reporting USACE analysis of dredge spoil samples
bottom sediment in Suisun Bay	88	1.409	Smith 1965] reporting USACE analysis of dredge spoil samples

<sup>a</sup> Derived from measurements of particle sizes carried by tributaries in 1959-60 ("delivered to the Bay/Delta system"), or in suspended sediment within the Bay ("delivered within the Bay") using a model for density of submerged sediments in a reservoir, with no compaction time. Calculated densities tend to decrease downstream through the system as larger particles (sand) are ground down to smaller ones (silt and clay). However, the calculated densities also increase significantly with time, due to compaction, as follows (in lb/ft<sup>3</sup>):

	<u>delivered to Bay/Delta</u>	<u>within Bay</u>
initially	48.84	45.05*
after 5 years	57.25	54.05
after 10 years	60.10	57.10
after 20 years	63.13	60.35

\* Note: Due to a math error, Smith 1965 incorrectly reported this as 47.05 lb/ft<sup>3</sup>.

The inconsistent use of these conversion factors can also lead to results that are not just inconsistent, but clearly erroneous. For example, Porterfield (1980) estimated the average sediment flow into the Bay and Delta in 1909-1966 to be 16,993 tons/day (Porterfield 1980, Table 30) (=5.6 million MT/yr); and used a conversion factor of 53.2 lb/ft<sup>3</sup> (=0.851 MT/m<sup>3</sup>) to report this as 23,598 yd<sup>3</sup>/day (Porterfield 1980, Table 31) (=6.6 million m<sup>3</sup>/yr). Ganju et al. (2008) then used a *different* conversion factor of 0.529 MT/m<sup>3</sup> to convert this back into a mass

estimate of 3.48 million MT/yr (Ganju et al. 2008 at p. 520). However, this is 2.1 million MT/yr less than Porterfield's original mass estimate and is clearly incorrect, a result of converting with one density value and then back-converting with another. Ganju et al. (2008) went on to use this erroneous value for sediment flows to calibrate a historic time series of daily sediment loads, which is intended for use in modeling simulations.<sup>6</sup>

Density values reported for sediments in different parts of the Bay show a wide range, from about 0.5 MT/m<sup>3</sup> in San Pablo Bay to nearly three times that, 1.4 MT/m<sup>3</sup>, in Suisun Bay (Table 7; Schoellhamer (pers. comm.) notes that there are several additional studies that measured Bay sediment densities that are not included in this table). Sediment densities in San Francisco Bay marshes may be lower than these numbers, though perhaps not as low as in more densely-vegetated Atlantic and Gulf Coast marshes: Greenbaum and Giblin (2000) reported sediment densities of 0.22-0.37 MT/m<sup>3</sup> in a *Spartina patens* marsh in Massachusetts, and Wheelock (2003) reported densities of 0.06-0.21 MT/m<sup>3</sup> in a Louisiana *S. patens* marsh. On the other hand, sand deposits in the Central Bay may exhibit higher sediment densities. The area-weighted mean of the average results for the main embayments in the Bay, based on U.S. Army Corps analysis of dredge spoil samples, is 0.76 MT/m<sup>3</sup>,<sup>7</sup> and a set of modeling studies in the 1960s produced similar sediment density estimates that ranged from about 0.72 to 0.80 MT/m<sup>3</sup>.<sup>8</sup> However, the mean sediment density value used in most Bay studies has been 0.53 MT/m<sup>3</sup>.<sup>9</sup> Thus, the frequent use of this possibly low sediment density value to represent average bay sediments may have resulted in considerable underestimates of the mass of sediment accumulated in the Bay, as well as possible overestimates of the amount of sediment deposited in tidal marshes and underestimates of the mass of sand (which typically has a higher density than sediments containing clay or silt—Smith 1965) that is removed by sand mining or carried into the Bay through the Golden Gate.

## Sediment Flows and Storage

A simple sediment model for the Bay below the high tide line exclusive of tidal marshes (the "subtidal Bay" as defined in these papers) is shown in Figure 2, and estimates of the quantities in the model as given by various studies (with inflows reported both as suspended load and total load) are compiled in Table 8. Inspection of Table 8 reveals numerous inconsistencies in these data, including different numbers reported for the same flow or storage over the same time period, and authors citing numbers from earlier papers that are in fact different from or absent from the earlier papers. Some of this is explained by the use of different density conversion

---

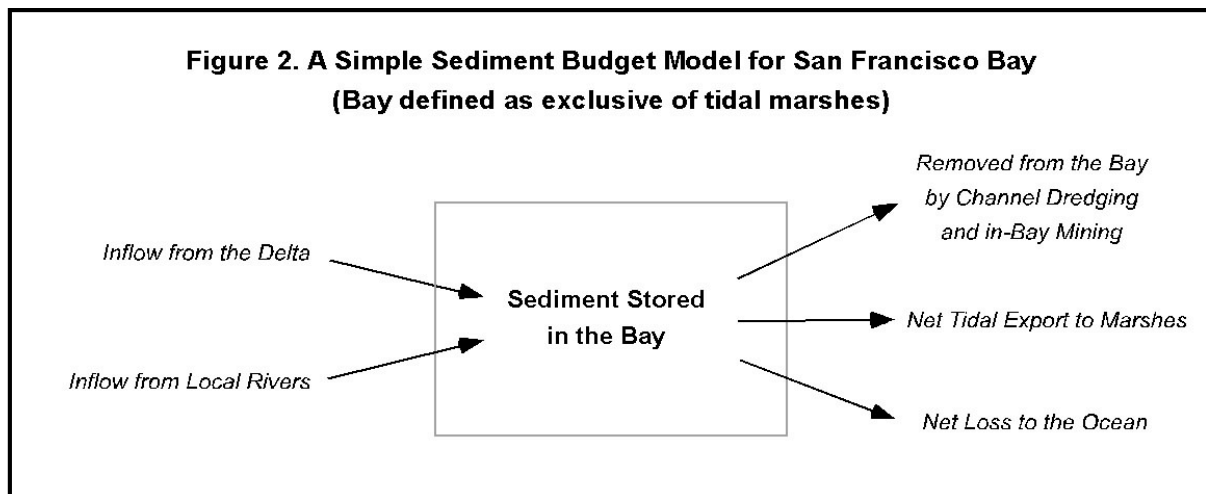
<sup>6</sup> Schoellhamer says that the incorrect value doesn't change the interpretations in the paper (D. Schoellhamer pers. comm.).

<sup>7</sup> Of course, the spoil samples may not fairly represent the distribution of sediment densities in the embayments. If the spoils were primarily taken from marina or back harbor sites where finer than average material accumulates, the use of spoils could produce an underestimate of mean sediment density; if primarily taken from channels with flowing water or tidal currents, where the bottom is of coarser than average material, they could produce an overestimate of mean density. Schoellhamer (pers. comm.) says that dredged spoils are denser than natural Bay sediment.

<sup>8</sup> These modeling studies produced estimates of the density of newly-deposited sediment. As deposits age, they compact and grow denser as shown in Footnote a in Table 7, with typical density increases of 15-20% in the first five years. Thus these studies probably underestimate mean sediment density.

<sup>9</sup> It's not clear where this number came from or what mensurative support it has. Its relatively wide use by researchers was probably initiated by Krone's 1979 chapter in the AAAS volume on San Francisco Bay. Ogden Beeman (1992) reported that it was "proposed by Schultz as a representative figure for the system. Actual values vary from around 25 pounds per cubic foot in areas of rapid deposition, to over 50 pounds per cubic foot at the mouth of Carquinez Strait."

factors that may not been selected with care, some by failing to convert properly between short tons and metric tons or between cubic yards and cubic meters, and some by typographic errors, but the largest share is probably due to authors incorrectly reporting or using numbers that were produced by earlier authors, and to not clearly explaining the derivation and significance of the numbers they use. Among the most common errors are not properly distinguishing between numbers for the following: suspended load vs. total load; inflow to the Bay vs. inflow to the Estuary (the Bay and Delta combined); Delta inflow vs. Delta outflow; Delta inflow vs. total inflow to the Estuary; and Delta outflow vs. total inflow to the Bay. As discussed further below, the estimates from Gilbert's (1917) study are almost always misrepresented when cited by later authors.



**Table 8. Estimates of Sediment Inflows, Outflows and Storage Changes in San Francisco Bay**

In mass or volume, whichever were provided by the listed sources. In some publications it is not entirely clear what some of the quantities refer to, for example whether a number for sediment inflow refers to inflow to the Delta or flow from the Delta to the Bay, or whether it includes the inflow from local rivers, or whether it refers to suspended sediment or to total sediment (suspended sediment plus bed load). These have been interpreted based on the context. As can be seen, quantities appear to frequently misquoted. If the original source of an estimate is listed here as a source, accurate citations of it are not. Where quantities were given in different units, these are shown in parentheses in the Source column, and converted using 1 short ton = 0.9072 metric tons, and 1 cubic yard = 0.7646 cubic meters.

Period	10 <sup>6</sup> MT/yr	10 <sup>6</sup> m <sup>3</sup> /yr	Source (quantities in original units; tons = short tons)
<b>INFLOWS</b>			
<b>Inflow from the Delta - Suspended Sediment</b>			
1909-1966	4.1		McKee et al. 2006 citing Porterfield 1980
1957-1959	3.3		Conomos & Peterson 1977 citing Porterfield et al. 1961
1960 conditions	3.0	5.7	Krone 1979 (3.35 x 10 <sup>6</sup> tons/yr) <sup>a</sup>
1955-1990	2.8	5.4	McKee et al. 2002 (7.0 x 10 <sup>6</sup> yd <sup>3</sup> /yr) citing Ogden Beeman 1992
1955-1990	2.4		McKee et al. 2006 citing Ogden Beeman 1992
1990 prediction	1.6	3.1	Krone 1979 (1.79 x 10 <sup>6</sup> tons/yr) <sup>a</sup>
1995-1998	2.1	4.0	McKee et al. 2002 (5.2 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1995-2003	1.2		McKee et al. 2006
1999-2002	0.6		Wright & Schoellhamer 2005
2020 prediction	1.1	2.1	Krone 1979 (1.22 x 10 <sup>6</sup> tons/yr) <sup>a</sup>
<b>Inflow from the Delta - Total Sediment</b>			
pre-1849		1.5	Gilbert 1917 (2 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
pre-1850	0.8		Wright & Schoellhamer 2004 citing Gilbert 1917
1849-1914 <sup>b</sup>		13.9-17.3	Gilbert 1917 (1.196-1.49 x 10 <sup>9</sup> yd <sup>3</sup> in 66 yr)
1850-1914		17.5	Smith 1965 (1.49 x 10 <sup>9</sup> yd <sup>3</sup> in 65 yr) citing Gilbert 1917
1852-1914		14	Van Geen & Luoma 1999 citing Gilbert 1917
1849-1914		14.1	Porterfield 1980 (18.4 x 10 <sup>6</sup> yd <sup>3</sup> /yr) and Schoellhamer et al. 2003 citing Gilbert 1917
peak mining yield	7.3		Wright & Schoellhamer 2004 citing Gilbert 1917
1915-64 prediction		12.2	Gilbert 1917 (800 x 10 <sup>6</sup> yd <sup>3</sup> in 50 yr)
1909-1959 <sup>g</sup>		3.9	Smith 1965 (5.133 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1909-1966	3.6		Schoellhamer et al. 2003] and Wright & Schoellhamer 2004 citing Porterfield 1980 <sup>c</sup>
1931		4.4	Porterfield 1980 citing Grimm 1931 (5.75 x 10 <sup>6</sup> yd <sup>3</sup> /yr) <sup>h</sup>
1954		2.6	Porterfield 1980 citing USACE 1954 (3.36 x 10 <sup>6</sup> yd <sup>3</sup> /yr) <sup>h</sup>
1955		3.1	Porterfield 1980 citing DWR 1955a,b (4 x 10 <sup>6</sup> yd <sup>3</sup> /yr) <sup>h</sup>
1960 conditions	3.3	6.1	Krone 1979 <sup>a,d</sup>
1960 conditions	4.4	8.3	Van Geen & Luoma 1999 citing Krone 1979
post-1964 prediction		6.1	Gilbert 1917 (8 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1955-1990 <sup>a</sup>	2.4	4.5	Ogden Beeman 1992 (2.622 x 10 <sup>6</sup> tons/yr, 5.88 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1955-1990	2.8		Schoellhamer et al. 2003] and Wright & Schoellhamer 2004 citing Ogden Beeman 1992 <sup>c</sup>
1955-1990	1.1		Schoellhamer et al. 2005
1990 prediction	1.7	3.3	Krone 1979 <sup>a,d</sup>
1990 conditions <sup>a</sup>	1.6	3.0	Ogden Beeman 1992 (1.75 x 10 <sup>6</sup> tons/yr, 3.93 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1995-1998		4.0	Schoellhamer et al. 2003 citing McKee et al. 2002 (5.2 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1995-2001		2.8	Schoellhamer et al. 2003 (3.6 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1995-2002	1.3		Schoellhamer et al. 2005
1995-2002 normal <sup>e</sup>	0.8		Schoellhamer et al. 2005
2020 prediction	1.2	2.2	Krone 1979 <sup>a,d</sup>
2035 prediction <sup>a</sup>	1.4	2.7	Ogden Beeman 1992 (1.57 x 10 <sup>6</sup> tons/yr, 3.52 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
"future"		1.5	Porterfield 1980 citing USACE 1954 (1.97 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
"future"		2.3	Porterfield 1980 citing DWR 1955a,b (3 x 10 <sup>6</sup> yd <sup>3</sup> /yr)

**Table 8 Continued. Estimates of Sediment Inflows, Outflows and Storage Changes in SF Bay**

Period	10 <sup>6</sup> MT/yr	10 <sup>6</sup> m <sup>3</sup> /yr	Source (quantities in original units; tons = short tons)
<b>Inflow from Local Rivers - Suspended Sediment</b>			
1909-1959	0.76		Porterfield 1980 (2,296 tons/d)
1909-1966	0.75		Porterfield 1980 (2,250 tons/d)
1957-1959	0.93	1.8	Smith 1965, Krone 1979 and Porterfield 1980 (2,830 tons/d) citing Porterfield et al. 1961 <sup>a</sup>
1957-1959	1.1		Porterfield 1980 (3,297 tons/d)
1957-1966	0.81		Porterfield 1980 (2,458 tons/d)
?	0.71		McKee et al. 2002 citing Abu-Saba & Tang 2000
"current"	0.75		McKee et al. 2002 (0.83 x 10 <sup>6</sup> tons/yr) citing Krone 1979
<b>Inflow from Local Rivers - Total Sediment</b>			
1909-1959 <sup>g</sup>	0.76	0.91	Smith 1965 and Porterfield 1980 (2,300 tons/d, 1.195 x 10 <sup>6</sup> yd <sup>3</sup> /yr) <sup>f</sup> citing Porterfield et al. 1961
1909-1959	0.83	0.99	Porterfield 1980 (2,514 tons/d, 3,548 yd <sup>3</sup> /d) <sup>i</sup>
1909-1966	0.81	0.97	Porterfield 1980 (2,452 tons/d, 3,467 yd <sup>3</sup> /d) <sup>i</sup>
1957-1959	1.0	1.9	Smith 1965, Krone 1979 and Porterfield 1980 (3,100 tons/d) <sup>f</sup> citing Porterfield et al. 1961 <sup>a,d</sup>
1957-1959	1.2	1.4	Porterfield 1980 (3,560 tons/d, 5,100 yd <sup>3</sup> /d) <sup>i</sup>
1957-1966	0.87	0.96	Porterfield 1980 (2,625 tons/d, 3,438 yd <sup>3</sup> /d) <sup>i</sup>
1955-1990	0.81		Schoellhamer et al. 2005
"current"	0.81		McKee et al. 2002 (0.89 x 10 <sup>6</sup> tons/yr) citing Krone 1979
1995-2002	1.5		Schoellhamer et al. 2005
1995-2002 normal <sup>e</sup>	0.9		Schoellhamer et al. 2005
<b>Total Inflow (from the Delta and Local Rivers Combined) - Suspended Sediment</b>			
1957-1959	4.2		Conomos & Peterson 1977 citing Porterfield et al. 1961
1960 conditions	4.0	7.5	Krone 1979 (4.38 x 10 <sup>6</sup> tons/yr) <sup>a</sup>
1990 prediction	2.6	4.8	Krone 1979 (2.82 x 10 <sup>6</sup> tons/yr) <sup>a</sup>
2020 prediction	2.0	3.9	Krone 1979 (2.25 x 10 <sup>6</sup> tons/yr) <sup>a</sup>
<b>Total Inflow (from the Delta and Local Rivers Combined) - Total Sediment</b>			
1849-1914	7.1	13.5	Ganju et al. 2008] citing Gilbert 1917 <sup>a</sup>
1909-1959 <sup>g</sup>		4.8	Smith 1965 (6.328 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1909-1966	3.5	6.6	Ogden Beeman 1992, McKee et al. 2002 and Ganju et al. 2008] (8.63 x 10 <sup>6</sup> yd <sup>3</sup> /yr) citing Porterfield 1980 <sup>a,j</sup>
1924-1960	4.5	8.5	Ogden Beeman 1992, Krone 1979 and McKee et al. 2002, 2006 (11.1 x 10 <sup>6</sup> yd <sup>3</sup> /yr) citing Schultz 1965
1960 conditions	3.3	6.3	Ogden Beeman 1992 and McKee et al. 2002, 2006 (8.23 x 10 <sup>6</sup> yd <sup>3</sup> /yr) citing Smith 1965 <sup>i</sup>
1960 conditions	4.2	8.0	Krone 1979 (10.5 x 10 <sup>6</sup> yd <sup>3</sup> /yr) <sup>a,d</sup>
?	4.0	7.6	Ogden Beeman 1992, McKee et al. 2002, 2006 and Levine-Fricke 2004 (10.0 x 10 <sup>6</sup> yd <sup>3</sup> /yr) citing USACE 1967
1955-1990 <sup>a</sup>	3.2	6.0	Ogden Beeman 1992, Krone 1996 (3.51 x 10 <sup>6</sup> tons/yr, 7.88 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1990 prediction	2.7	5.2	Krone 1979 <sup>a,d</sup>
1990 conditions <sup>a</sup>	2.0	4.5	Ogden Beeman 1992, Krone 1996 (2.64 x 10 <sup>6</sup> tons/yr, 5.93 x 10 <sup>6</sup> yd <sup>3</sup> /yr)
1990-2006	2.2		Ganju et al. 2008
2020 prediction	2.2	4.1	Krone 1979 <sup>a,d</sup>
2035 prediction <sup>a</sup>	2.2	4.2	Ogden Beeman 1992, Krone 1996 (2.46 x 10 <sup>6</sup> tons/yr, 5.52 x 10 <sup>6</sup> yd <sup>3</sup> /yr)

**Table 8 Continued. Estimates of Sediment Inflows, Outflows and Storage Changes in SF Bay**

Period	10 <sup>6</sup> MT/yr	10 <sup>6</sup> m <sup>3</sup> /yr	Source (quantities in original units; tons = short tons)
<b>OUTFLOWS</b>			
<b>Removed by Channel Dredging and in-Bay Mining</b>			
1960 conditions		0.8	Krone 1979 ( $1.0 \times 10^6$ yd <sup>3</sup> /yr)
1955-1990		0.36	Ogden Beeman 1992 ( $16.6 \times 10^6$ yd <sup>3</sup> in 35 yr)
1955-1990		0.31	Ogden Beeman 1992, Krone 1996 ( $0.41 \times 10^6$ yd <sup>3</sup> /yr)
1955-1990	0.98		Schoellhamer et al. 2005
1995-2002	3.1		Schoellhamer et al. 2005
1995-2002 normal <sup>e</sup>	2.8		Schoellhamer et al. 2005
<b>Net Tidal Export to Marshes</b>			
1955-1990		≤0.13	Ogden Beeman 1992 ( $≤0.17 \times 10^6$ yd <sup>3</sup> /yr)
1955-2002	0.19		Schoellhamer et al. 2005
<b>Net Loss to Ocean</b>			
1849-1914		0.6	Gilbert 1917 ( $50 \times 10^6$ yd <sup>3</sup> in 66 yr)
1915-64 prediction		0.6	Gilbert 1917 ( $40 \times 10^6$ yd <sup>3</sup> in 50 yr)
1924-1960		2.5	Conomos & Peterson 1977, Ogden Beeman 1992 and Levine-Fricke 2004 (30% of $11.1 \times 10^6$ yd <sup>3</sup> /yr) citing Schultz 1965
?		3.2	Levine-Fricke 2004 (42% of $10 \times 10^6$ yd <sup>3</sup> /yr) citing USACE 1967
1957-1959	0.25		Conomos & Peterson 1977 (6% of $4.2 \times 10^6$ MT/yr)
1960 conditions		3.7	Krone 1979 ( $4.9 \times 10^6$ yd <sup>3</sup> /yr) <sup>l</sup>
1960 conditions		3.1	Krone 1996 ( $4.0 \times 10^6$ yd <sup>3</sup> /yr) <sup>l</sup> citing Krone 1979
1960 conditions		4.0	Levine-Fricke 2004 (50% of $10.4 \times 10^6$ yd <sup>3</sup> /yr) citing Krone 1979
1955-1990		2.6	Ogden Beeman 1992, Krone 1996 ( $3.37 \times 10^6$ yd <sup>3</sup> /yr)
1955-1990	2.1		Schoellhamer et al. 2005
1995-2002	1.3		Schoellhamer et al. 2005
1995-2002 normal <sup>e</sup>	1.1		Schoellhamer et al. 2005
<b>CHANGE IN STORAGE</b>			
1849-1914		13.3	Gilbert 1917 ( $1.146 \times 10^9$ yd <sup>3</sup> in 66 yr)
1915-64 prediction		11.6	Gilbert 1917 ( $760 \times 10^6$ yd <sup>3</sup> in 50 yr)
1855-1956 <sup>k</sup>		4.6	Smith 1965 ( $6.06 \times 10^6$ yd <sup>3</sup> /yr)
1870-1896 <sup>k</sup>		6.0	Krone 1979 ( $210.2 \times 10^6$ yd <sup>3</sup> in 27 yr)
1897-1922		3.5	Krone 1979 ( $4.62 \times 10^6$ yd <sup>3</sup> /yr)
1923-1950		3.5	Krone 1979 ( $4.63 \times 10^6$ yd <sup>3</sup> /yr)
1960 conditions		3.5	Krone 1979 ( $4.6 \times 10^6$ yd <sup>3</sup> /yr) <sup>l</sup>
1960 conditions		4.2	Krone 1996 ( $5.5 \times 10^6$ yd <sup>3</sup> /yr) <sup>l</sup> citing Krone 1979
1955-1990	-1.4		Schoellhamer et al. 2005
1955-1990		3.1	Ogden Beeman 1992, Krone 1996 ( $4.1 \times 10^6$ yd <sup>3</sup> /yr) <sup>m</sup>
1995-2002	-1.8		Schoellhamer et al. 2005
1995-2002 normal <sup>e</sup>	-2.4		Schoellhamer et al. 2005

<sup>a</sup> Volume estimates based on conversion factor of  $33 \text{ lb/ft}^3 = 0.529 \text{ MT/m}^3$ .

<sup>b</sup> The lower figure excludes the sediment deposited on tidal marshes in the Bay; the higher figure includes these plus the sediments deposited in Sacramento Valley basins and Delta marshes.

<sup>c</sup> Estimated from Schoellhamer et al.'s (2003) Figure 6 and Wright & Schoellhamer's (2004) Figure 2.

<sup>d</sup> Based on suspended sediment data and bed load = 0.065 of total.

<sup>e</sup> "Normal year" conditions, that is, the period with 2 unusually wet years deleted.

<sup>f</sup> These quantities are from Smith's (1965) Table 5 and Table 12; quantities calculated from his numbers on page 677 are different due to round-off and apparent transcription error.

<sup>g</sup> Estimate based on 1957-59 sediment flows adjusted to 1909-59 water flows, with 1960 levels of water withdrawals from the Delta.

<sup>h</sup> Might include inflows to Delta, not flows from Delta into Bay.



- <sup>i</sup> Volume estimates apparently were intended to be based on a conversion factor of  $53.2 \text{ lb/ft}^3 = 0.852 \text{ MT/m}^3$  (Porterfield 1980 at pages 5 and 88). However, back-calculating from Porterfield's Tables 30 and 31 yields conversion factors of 51.2-53.9  $\text{lb/ft}^3$ , and in one case (presumably a calculation error), 64.7  $\text{lb/ft}^3$ .
- <sup>j</sup> The original authors calculated these quantities based on sediment inflows to the Delta, and thus they include export from and deposition within the Delta.
- <sup>k</sup> Based on changes in water depth with no adjustment for sea level rise, according to Krone (1979).
- <sup>l</sup> As discussed in footnote 2 of this report, Krone's (1979) Figure 6 shows erroneous or at least confusing numbers for the annual deposition rate and the net outflow to the ocean, which led to later mis-citations by Krone and others.
- <sup>m</sup> Includes net deposition in tidal marshes of  $\leq 0.13 \times 10^6 \text{ m}^3/\text{yr}$  (Ogden Beeman 1992 at page 20).
- <sup>n</sup> Volume estimates based on conversion factor of  $0.85 \text{ MT/m}^3 (=53.2 \text{ lb/ft}^3)$ .

## Review of Sediment Budgets and Sediment Load Estimates

Gilbert's (1917) sediment budget (Table 1) is the starting point for our understanding of changes in sediment flows and sedimentation in the Bay system, and it is cited by nearly all researchers in this area, but rarely is it cited accurately. Contrary to most citations, Gilbert did not develop estimates of the sediment flow into the Delta, the Bay or the Estuary. Because of the central role of Gilbert's work in our concept of sediment flows in this system, however, it is worth taking a few minutes to understand what he did do.

Gilbert considered sediment volumes in several categories (note: the terms used here to identify these categories were not specifically used by Gilbert):

- **Waste:** Material removed from its original undisturbed placement in the Sierra Nevada by mining, other human activities, or natural wastage of the land surface between 1849 and 1914, which we will call Waste. Seventy percent of this, by Gilbert's estimate, was mining debris, with the rest derived from agriculture, overgrazing, road building, etc.
- **Upland Deposits:** That portion of Waste that had not yet reached the Delta by 1914, consisting of Mountain Deposits, Piedmont Deposits, River Bed Deposits, and Flood Basin Deposits, with the exception that deposits in the beds of rivers within the Delta were included in River Bed Deposits. The last component, Flood Basin Deposits, was not estimated by Gilbert.
- **Local River Sediment:** Gilbert neither mentioned nor considered this component, sediment that is carried in by local rivers and streams that are tributary to the Bay, but it is an important part of the Bay's sediment budget. Local River Sediment was probably larger during the period covered by Gilbert's work than it is today, as the local watersheds were also subject to the erosive developments of agriculture, overgrazing, road and trail building, and some mining activities, as well as urbanization, and there were fewer dams in them, but probably accounted for a smaller fraction of the sediment delivered to the Bay.
- **Estuarine Deposits:** That portion of Waste that could be found within the boundaries of the Estuary in 1914, consisting of Bay Deposits, Delta Marsh Deposits and Bay Marsh Deposits. Gilbert estimated Bay Deposits from changes in bathymetry shown on successive USC&GS charts, and did not estimate the volume of marsh deposits.
- **Outflow to Ocean:** Gilbert's estimate of this was essentially a guess unsupported by any evidence. Even today, we have no way of directly estimating this quantity, but calculate it as what remains in a sediment budget after making our best estimates of all other components.

Gilbert's sediment budget thus differs substantially in form from the budgets constructed later, and sediment inflows at the margins of the Bay or Estuary cannot be determined from the estimates that Gilbert provided. For example, sediment carried into the Bay in Delta Outflow should equal Waste minus Upland Deposits and Delta Marsh Deposits, but out of these Gilbert did not estimate Flood Basin Deposits or Delta Marsh Deposits. The sediment in Delta Outflow should also equal the sum of Bay Deposits, Bay Marsh Deposits and Outflow to Ocean minus Local River Sediment, but Gilbert did not estimate Bay Marsh Deposits or Local River sediment, and only guessed at Outflow to Ocean. At best then, we can only specify a rough upper and lower bound for the quantities that we are interested in.

In addition, the basic accuracy of Gilbert's estimates is probably much lower than it is for more modern estimates. Gilbert's estimates of the components of Waste consist of combinations, in various proportions, of rough approximations, measurements of uncertain accuracy, comparisons, extrapolations, and possibly shrewd but unverifiable guesses. The confidence intervals on these results should be quite large. Also the differences between the bulk density of undisturbed sediments in the Sierra Nevada before they were dug out by miners (typically 1-2 MT/m<sup>3</sup>), and the bulk density of those same sediments after they've been deposited in the Bay (typically = 0.5-1.0 MT/m<sup>3</sup>), are unaccounted for in Gilbert's budget, and if included could modify some of the residual quantities several-fold.

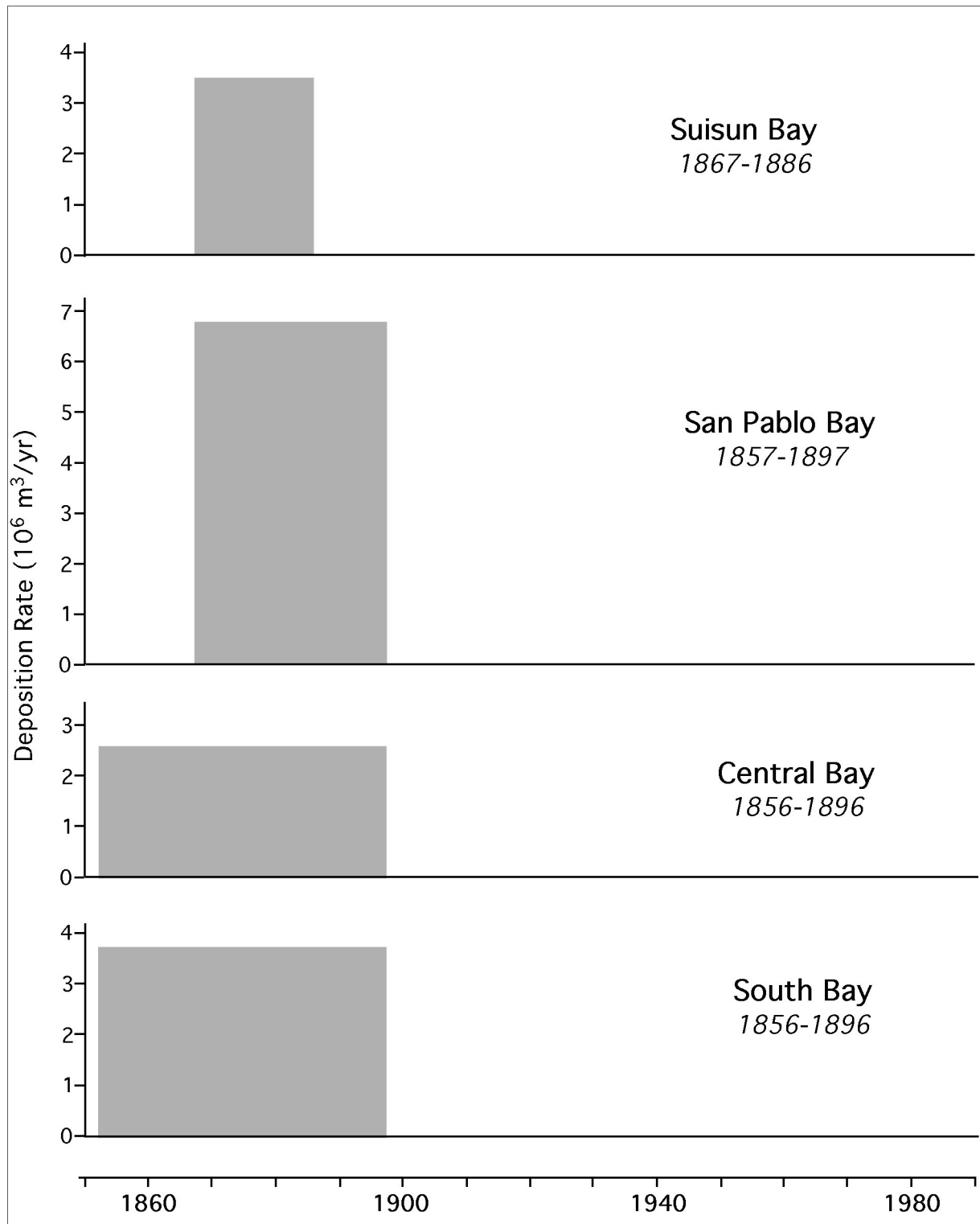
Gilbert's estimates of sediment deposition in different parts of the Bay, based on changes in charted bathymetry, are shown in Figure 3. The pattern he found of substantial net deposition in all parts of the Bay including the southern Bay is contrary to the finding of later analyses based on the same chart data. These are shown in Figures 4-6, which found strong deposition in the northern part of the Bay and little or no deposition or net erosion in the Central and South bays. All of these later analyses indicate substantially lower deposition rates than Gilbert estimated (Table 9), which could significantly alter his sediment budget (Table 1).

**Table 9. Overall Annual Deposition Rates in San Francisco Bay in ca. 1860-1890**

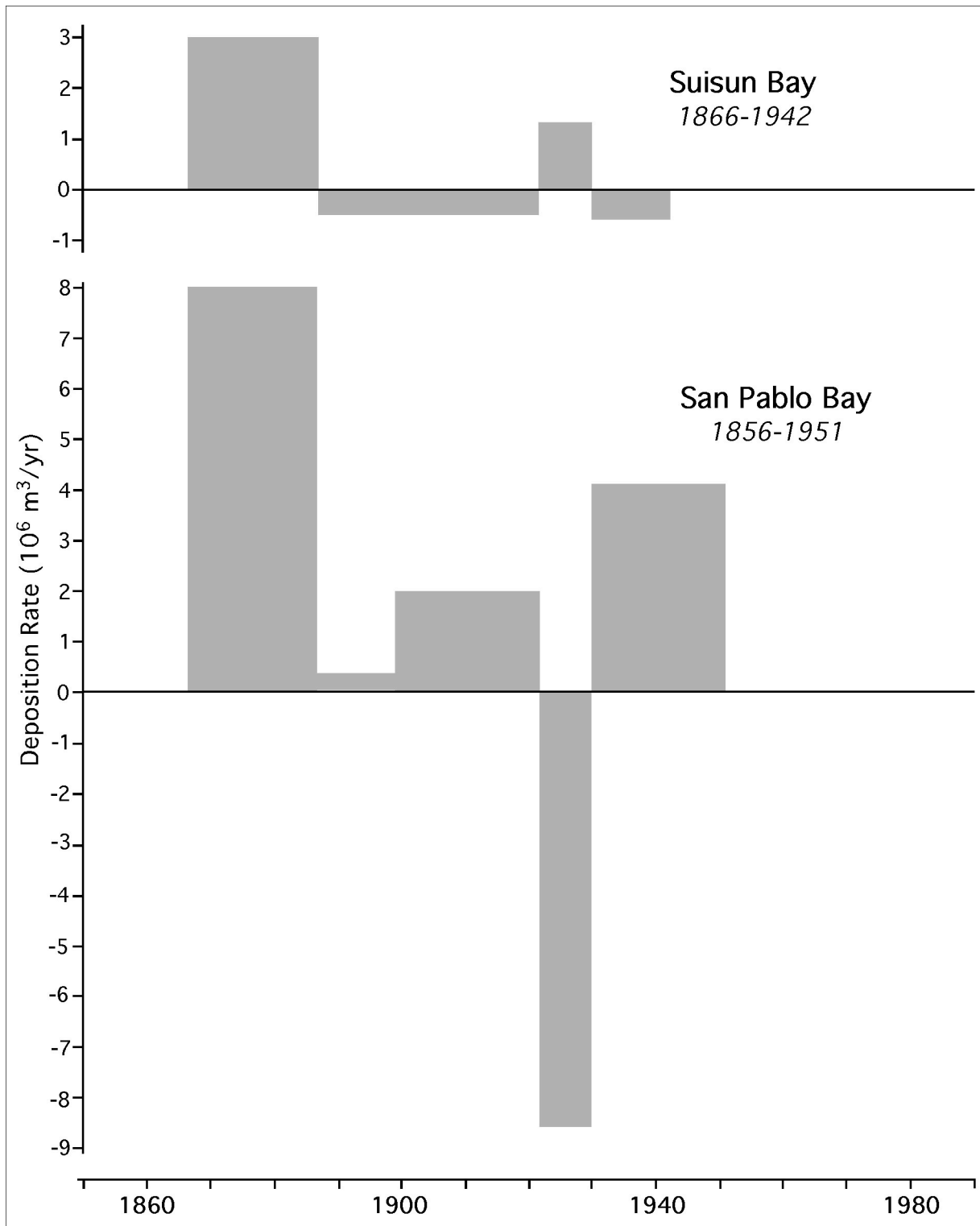
Study	Period	Deposition 10.6 m <sup>3</sup> /yr
Gilbert 1917	1857-1897	13.5
Smith 1965	1855-1898	10.1
Krone 1979	1870-1896	7.7
Jaffe et al. 1998, Cappiella et al. 1999, Foxgrover et al. 2004 and Fregoso et al. 2008; the period 1867-87 is overlapped by the earliest period analyzed in each of these studies.	1867-1887	10.0

The various assessments of sediment deposition and erosion rates shown in Figures 3-6 differ in other ways. Most striking are the two sets of analyses for the period since the 1940s-1950s. Krone (1996) reported net deposition in all parts of the Bay between 1955 and 1990 (Figure 5). However, more recent studies by USGS researchers (Jaffe et al. 1998; Cappiella et al. 1999; Foxgrover et al. 2004; Fregoso et al. 2008) report net erosion in all parts of the Bay between 1947-1956 and 1980-1990 (Figure 6).

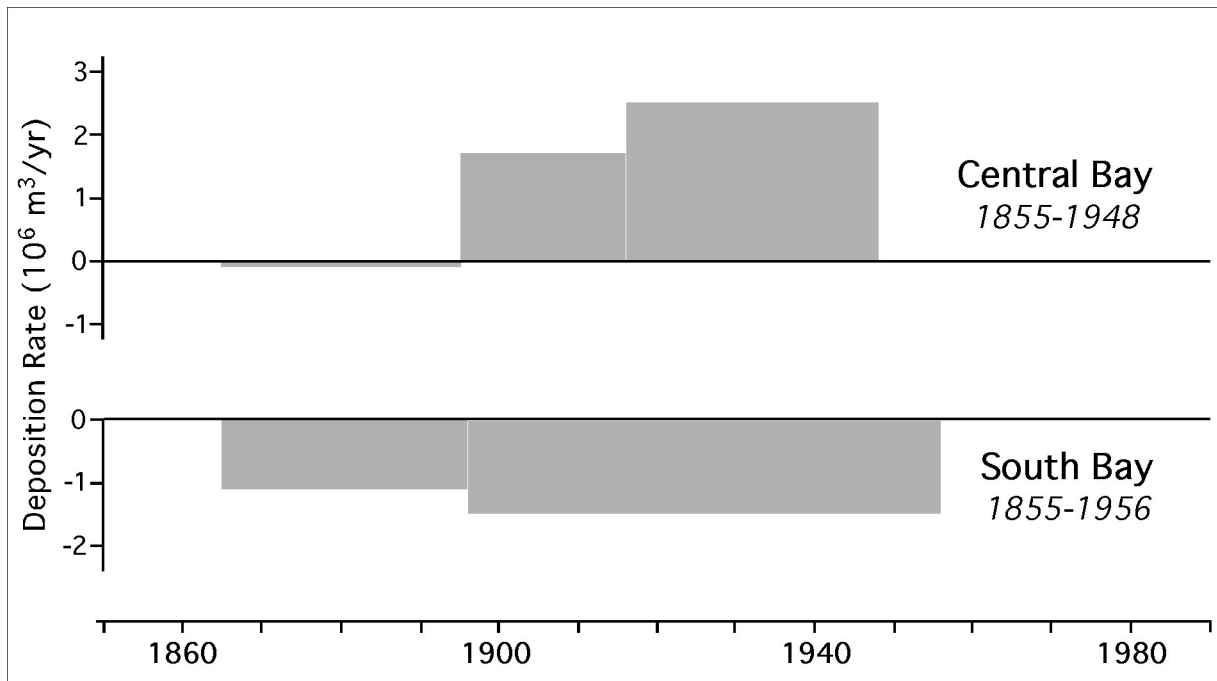
**Figure 3. Sediment Deposited in San Francisco Bay 1856-1897, from Gilbert 1917**



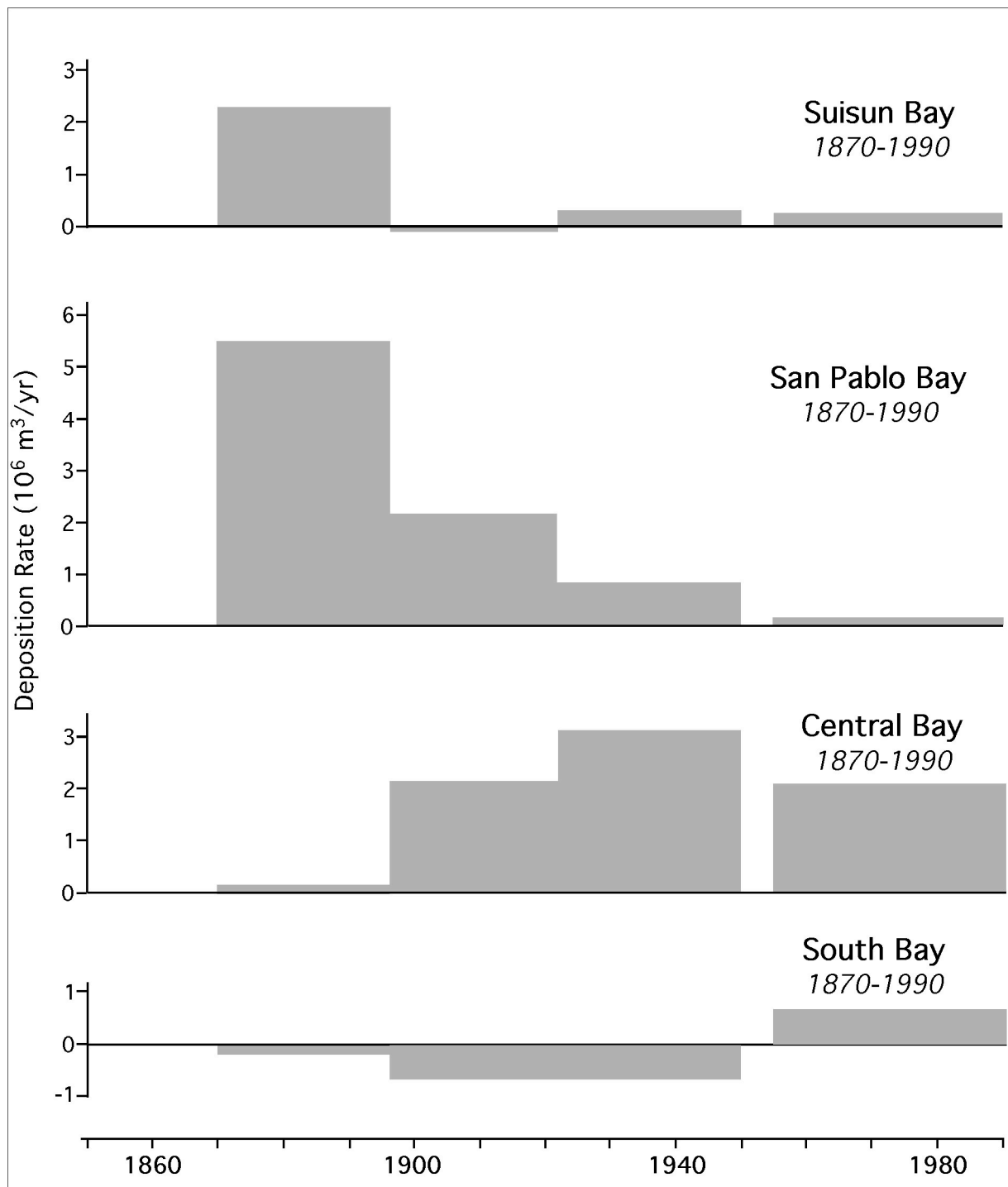
**Figure 4a. Sediment Deposited in San Francisco Bay 1855-1956, from Smith 1965**



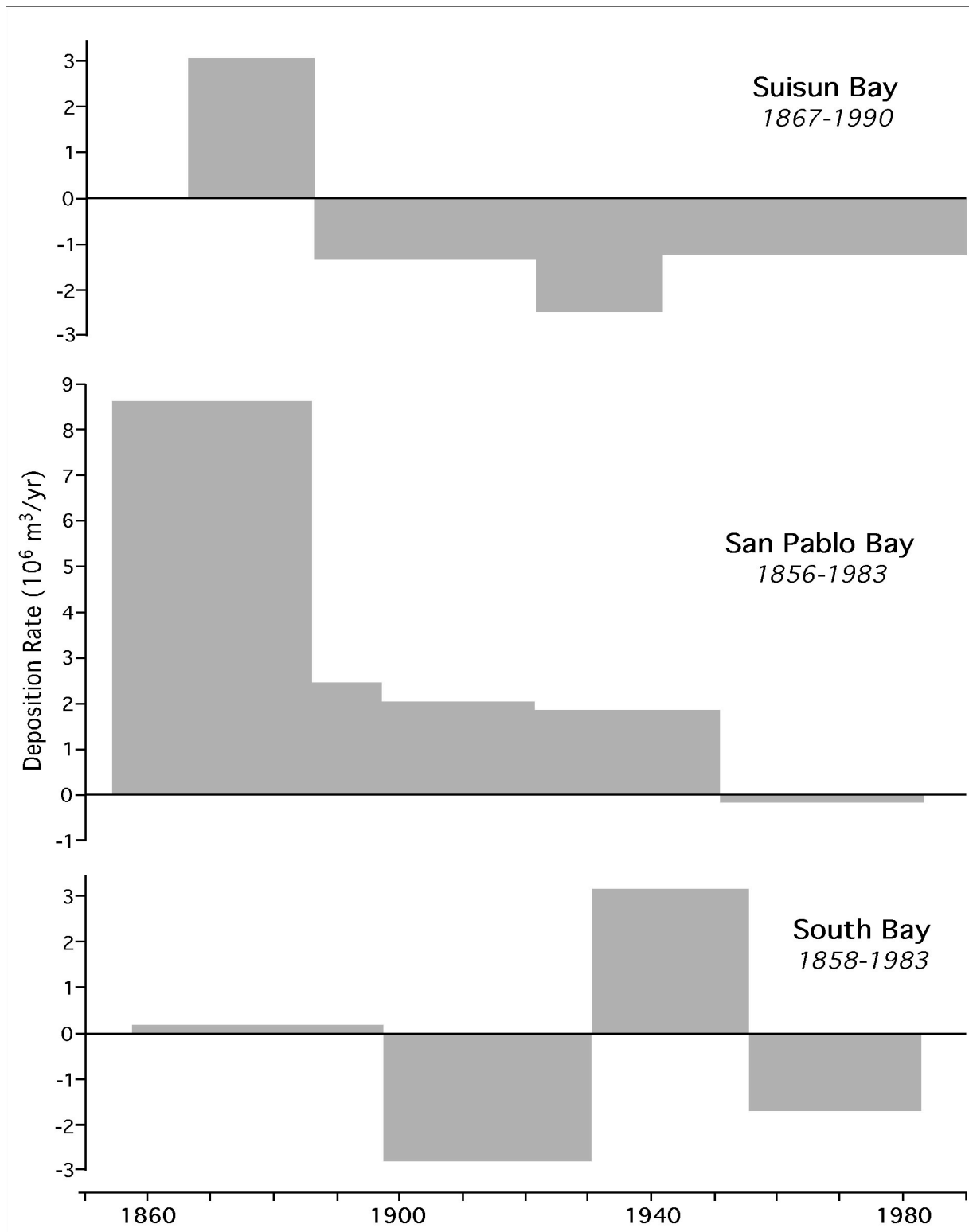
**Figure 4b. Sediment Deposited in San Francisco Bay 1855-1956, from Smith 1965**



**Figure 5. Sediment Deposited in San Francisco Bay 1870-1990, from Krone 1979 and Krone 1996**



**Figure 6. Sediment Deposited in San Francisco Bay 1856-1990, from Cappiella et al. 1999 (Suisun Bay), Jaffe et al. 1998 (San Pablo Bay) and Foxgrover et al. 2004 (South Bay)<sup>10</sup>**



<sup>10</sup> A study addressing the Central Bay (Fregoso et al. 2008) was released too late to be included in this figure.

Despite the limitations of the Bay's sediment budgets and problems with the reporting and comparing of sediment flow estimates, some very general patterns are clear. In the late 19th century, sediment flows to the Bay were greatly increased over prior, natural levels due to mining, agricultural development and other activities. With changes in these activities, and with the construction of dams and impoundments that serve as traps to retain sediment, the delivery of sediment to the Bay has declined. The quantity delivered may be near or approaching the natural background levels that Gilbert (1917) estimated for the pre-mining period (see Table 8). Sediment deposition in the Bay also declined rapidly at first, but evidence of subsequent decline is lacking. Changing sea levels may increase the need for sediment, if marshes and mudflats are to keep pace with the rising sea. However, calculations suggest that despite the declining inflows there is still adequate sediment delivered to the Bay to meet this need (Van Geen and Luoma 1999).

Sediment availability, the size of water flows, and the trapping of sediment by dams are major influences on the quantity of sediment carried into the Bay. Changes in average flows and peak flows are caused by freshwater storage and use, by increases in the portions of the watershed that are covered by hardened surfaces due to urban development, by alterations in watercourses, by dam operations, and by climate change. In the last half of the 19th century, mining, land clearing and other activities increased both runoff rates and sediment load (Gilbert 1917). Flood control levees constructed along major watercourses reduced over-bank flooding and the deposition of sediment on floodplains, and this further increased the delivery of suspended sediments downstream. Starting in the 1940s, extensive dam construction caused the settling and retention of sediment in impoundments, which reduced the transport of suspended sediment downstream of the dams (Krone 1979). Water diversions, also increasing more rapidly since the early 1940s, also divert sediments and reduce the loadings to the Bay (Krone 1979). Most observers believe that water storage and use has substantially decreased the flow of water into the Bay relative to pre-1850 conditions (e.g. Nichols et al. 1986). Peak flows have mostly been reduced by dams and impoundments, although hardened surfaces and watercourse channelization may have increased peak flows in some local watersheds. In some areas, summer flows have been increased by the storage and delivery of water for agricultural, golf course and domestic irrigation, and by mandatory minimum releases of water to sustain fisheries or improve fish habitat.

Relevant climate change effects include changes in the timing, amount and type of precipitation, the amount of snow pack, the timing of snow melt and possibly the rate of evapotranspiration. Changes in the watershed over the past several decades have included increases in the frequency and intensity of extreme rainfall events and a shift toward earlier snow melt and earlier runoff peaks (Dettinger et al. 1995; Lund et al. 2007). Anthropogenic climate change is expected to continue these trends and to increase the year-to-year variability in precipitation, increase the frequency of large winter storms, and advance and compress the period of snowmelt, increasing the frequency and strength of peak winter runoff events (Lund et al. 2007). The overall net effect on the amount of sediment delivered to the Bay is unclear.

As noted earlier, changes in sediment inputs to the Bay can have a variety of effects. An increase in sediment inputs, as occurred in the late 19th century, promotes higher deposition rates, shoaling, marsh accretion, rapid burial of contaminants and nutrients, and an increased need for channel dredging. Conversely, a reduction in sediment inputs, which has occurred since the 19th century peak, tends to result in the erosion of bottom sediments, shoal areas and marshes, expose buried contaminants and nutrients, and reduce the need for channel dredging. If recent analyses are correct in finding continuing declines in sediment inflows (McKee et al.



2002, 2006) and net erosion of the Bay bottom in recent decades (Jaffe et al. 1998; Cappiella et al. 1999; Foxgrover et al. 2004; Fregoso et al. 2008), this will hamper efforts to open and restore diked areas as tidal marsh. These efforts become more challenging with reductions in sediment supply, since many of the diked areas are low in elevation and would need to accumulate sediment in order to support the growth of marsh vegetation, while others may suffer net erosion when invaded by Bay waters with little suspended sediment. Rising sea levels add to this problem.

## **Impacts of Suspended Sediment**

Besides activities and effects in the watershed that increase the amount of sediment delivered to the Bay in tributary waters, several activities locally inject substantial quantities of sediment into the water column and raise sediment concentrations to relatively high levels for a time. These include dredging and the in-Bay disposal of dredge materials, shell and sand mining, bottom trawling for fisheries or research purposes, and boat movements, particularly of large commercial vessels when they are maneuvering near wharves and their keels are close to the sediment surface. Suspended sediment can also be injected into the Bay via wastewater and storm water outfalls (L. McKee pers. comm.). The *potential* for impacts on organisms from large increases in sediment concentrations in the water column is well-documented, and include clogging the gills of fish and invertebrates; changing the behavior of adult fish; providing cover for prey species and reducing predation; and reducing light penetration, photosynthesis and the productivity and growth of eelgrass, seaweeds and phytoplankton (O'Connor 1991; ABP Research 1999; Levine-Fricke 2004). The assessment of activities that inject sediment into the water column thus hinges on the question of whether the sediment concentrations are elevated high enough for long enough to have an effect. In San Francisco Bay, the injection of sediment occurs in the context of a shallow bay with naturally turbid waters due to frequent wind and current stirring of bottom sediments into the water column, as well as the periodic discharge of sediment-laden runoff, especially in the spring and during and after storm events. The volume of bottom sediment resuspended in the water column of San Francisco Bay each year has been estimated at approximately 75 million cubic meters (Krone 1974, cited in LTMS 1998), 130 million cubic meters (Segar 1990) and 220 million cubic meters (San Francisco Estuary Project 1992, cited in LTMS 1998), quantities that dwarf the estimated 4-8 million cubic meters of sediment delivered by rivers each year (Table 8).

When sediment is injected into the water column it spreads out and downstream from the source in a sediment plume. The larger and heavier particles quickly settle to the bottom near the source, but fine material may remain suspended for some time and travel some distance before settling. A "worst case" suspended sediment field around a dredge or other source could have suspended sediment concentrations of up to 500 mg/L at up to 500 meters from the source (LaSalle 1990). Concentrations are generally much lower than this, and maximum concentrations are generally restricted to the lower part of the water column within 50-100 meters of the source. Such turbidity plumes are short-lived once the activity generating the sediment has stopped. Maximum levels of up to a few hundred mg/L are expected during major dredging operations in San Francisco Bay (Hirsch et al. 1978). In comparison, total suspended solids of up to 1,000 mg/L have been measured at turbidity maxima in northern San Francisco Bay (O'Connor 1991).

Suspended sediment concentrations were measured at 58-743 mg/L along the bottom at 50 meters downstream of an operating hopper dredge in San Francisco Bay, and were generally in the range of 70-130 mg/L 50 meters from a bucket dredge (Hanson & Walton 1990). Wakeman

et al. (1975) measured suspended sediment concentrations around dredging operations in San Francisco Bay and compared these to levels needed to produce toxic effects in a few Bay species of fish, shrimp and mussel, and found that none of the organisms were sensitive to the typical dredge-produced turbidity conditions. Other tests on mussels, shrimp, a polychaete, an amphipod, an isopod and fish from San Francisco Bay found them tolerant of sediment loads "much in excess of" a few hundred mg/L for periods of up to 10 days (Hirsch et al. 1978). Concentrations measured at and near the Alcatraz dump site ranged from 10-50 mg/L (Segar 1990), well below the levels at which effects on organisms were observed (Wakeman et al. 1975). A workshop review found no evidence for any harmful effects on anadromous fish from coming into contact with dredge-associated sediment plumes (Simenstad 1990). Overall there appears to be no evidence that, chemical contaminants aside, the generation of sediment plumes by various dredging, mining or other activities poses a significant risk to organisms in a naturally turbid estuary like San Francisco Bay.

## **Acknowledgments**

I thank Dave Schoellhamer (U.S. Geological Survey) for generously copying a number of hard-to-get reports for me, and he and Lester McKee (San Francisco Estuary Institute) for their helpful reviews.

## **Literature Cited**

- Abu-Saba, K.E. and L.W. Tang. 2000. Watershed management of mercury in the San Francisco Bay Estuary: Draft total maximum daily load report to U.S. EPA. San Francisco Regional Water Quality Control Board, Oakland, CA.
- Cappiella, K, Malzone, C, Smith, R.E., Jaffe, B.E., 1999. Sedimentation and bathymetry changes in Suisun Bay, 1867– 1990: U.S. Geological Survey Open-File Report 99-563.
- Conomos, T.J. and D.H. Peterson. 1977. Suspended particle transport and circulation in San Francisco Bay: an overview. Pages 82-97 in: Wiley, M. (ed.), *Estuarine Processes, Volume II. Circulation, Sediments and Transfer of Material in the Estuary*. Academy Press, Inc, New York.
- Dettinger, M.D., D.R. Cayan and D.H. Peterson. 1995. Sierra Nevada runoff into San Francisco Bay— why has it come earlier recently? *Interagency Ecological Program Newsletter*, Summer 1995: 1-3.
- DWR. 1955a. Sedimentation, Appendix G in: Report to the Water Project Authority of the State of California on the Feasibility of the Construction by the State of Barriers in the San Francisco Bay System, California Department of Water Resources, Sacramento, CA.
- DWR. 1955b. Report to the Water Project Authority of the State of California on the Feasibility of the Construction by the State of Barriers in the San Francisco Bay System, California Department of Water Resources, Sacramento, CA.
- Foxgrover, A.C., Higgins, S.A., Ingraca, M.K., Jaffe, B.E. and Smith, R.E. 2004. Deposition, erosion, and bathymetric change in South San Francisco Bay: 1858–1983: U.S. Geological Survey Open-File Report 2004–1192. <http://pubs.usgs.gov/of/2004/1192>
- Fregoso, T.A., A.C. Foxgrover and B.E. Jaffe. 2008. Sediment deposition, erosion, and bathymetric change in central San Francisco Bay: 1855-1979. U.S. Geological Survey Open-File Report 2008-1312. <http://pubs.usgs.gov/of/2008/1312>

Ganju, N.K., N. Knowles and D.H. Schoellhamer. 2008. Temporal downscaling of decadal sediment load estimates to a daily interval for use in hindcast simulations. *J. Hydrology* 349(3-4): 512-523.

Gilbert, G.K. 1917. Hydraulic Mining Debris in the Sierra Nevada. U.S. Geological Survey Professional Paper 105.

Greenbaum, A. and A. Giblin. 2000. Differences in properties of salt marsh sediment between hayed and reference sites. *Biol. Bull.* 199: 225-226.

Grimm, C.I. 1931. Study of tidal currents and silt movements in the San Francisco Bay Area, with particular reference to the effect of a salt water barrier upon them. U.S. Corps of Engineers, Special Report (Appendix D, House Document 191, 71st Congress, 3rd Session).

Hanson, C.H. and C.P. Walton. 1990. Potential effects of dredging on early life stages of Striped Bass (*Morone saxatilis*) in the San Francisco Bay area: an overview. Pages 38-56 in: Simenstad, C.A. (ed.), Effects of Dredging on Anadromous Pacific Coast Fishes. Workshop Proceedings, Seattle, September 8-9, 1988. Washington Sea Grant Program, University of Washington, Seattle, WA.

Hanson, C.H., J. Coil, B. Keller, J. Johnson, J. Taplin and J. Monroe. 2004. Assessment and Evaluation of the Effects of Sand Mining on Aquatic Habitat and Fishery Populations of Central San Francisco Bay and the Sacramento-San Joaquin Estuary. Prepared for Hanson Aggregates Mid-Pacific, Inc., RMC Pacific Materials, Inc. and Jerico Products, Inc./Morris Tug and Barge. Hanson Environmental, Inc., Walnut Creek, CA.

Hirsch, N.D., L.D. DiSalvo and R. Peddicord. 1978. Effects of dredging and disposal on aquatic organisms. Technical Report DS-78-5, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Jaffe, B.E., R.E. Smith and L.Z. Torresan. 1998. Sedimentation and bathymetric change in San Pablo Bay: 1856–1983: U.S. Geological Survey Open-File Report 98–759.

Jaffe, B.E., R.E. Smith and A.C. Foxgrover. 2007. Anthropogenic influence on sedimentation and intertidal mudflat change in San Pablo Bay, California: 1856-1983. *Estuarine, Coastal and Shelf Science* 73: 175-187.

Krone, R.B. 1987. A method for simulating historic marsh elevations. Pages 316-323 in: Proceedings of the ASCE Conference on Coastal Sediments 87, New Orleans, LA.

Krone, R.B. 1979. Sedimentation in the San Francisco Bay system. Pages 85-96 in: Conomos, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco.

Krone, R.B. 1996. Recent sedimentation in the San Francisco Bay system. Pages 63-68 in: Hollibaugh, J.T. (ed.), San Francisco Bay: The Ecosystem. Pacific Division of the American Association for the Advancement of Science, San Francisco.

LaSalle, M.W. 1990. Physical and chemical alterations associated with dredging: an overview. Pages 1-12 in: Simenstad, C.A. (ed.), Effects of Dredging on Anadromous Pacific Coast Fishes. Workshop Proceedings, Seattle, September 8-9, 1988. Washington Sea Grant Program, University of Washington, Seattle, WA.

Levine-Fricke. 2004. Framework for Assessment of Potential Effects of Dredging on Sensitive Fish Species in San Francisco Bay. Final Report 001-09170-00 prepared for the U.S. Army Corps of Engineers. LFR Levine-Fricke, Emeryville, CA.

Lionberger, M.A. 2003. A tidally-averaged sediment transport model of San Francisco Bay, California. MS

thesis, Department of Civil and Environmental Engineering, University of California, Davis, CA.

LTMS. 1998. Long-Term Management Strategy for Bay Area Dredged Material Final Environmental Impact Statement/Environmental Impact Report. <http://www.spn.usace.army.mil/ltms/toc.html>

Lund, J., E. Hanak, W. Fleenor, R. Howitt, J. Mount and P. Moyle. 2007. Envisioning Futures for the Sacramento-San Joaquin Delta. Public Policy Institute of California, San Francisco.

McKee, L., N. Ganju, D. Schoellhamer, J. Davis, D. Yee, J. Leatherbarrow and R. Hoenicke. 2002. Estimates of suspended-sediment flux entering San Francisco Bay from the Sacramento and San Joaquin Delta. San Francisco Estuary Institute, Oakland, CA.

McKee, L., N. Ganju and D. Schoellhamer. 2006. Estimates of suspended-sediment entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California. *Journal of Hydrology* 323: 335-352.

Nichols, F.H., Cloern, J.E., Luoma, S.N. and D.H. Peterson. 1986. The modification of an estuary. *Science* 231: 525-648.

O'Connor, J.M. 1991. Evaluation of turbidity and turbidity-related effects on the biota of the San Francisco Bay-Delta estuary. A report for the U.S. Army Corps of Engineers. The San Francisco Bay-Delta Aquatic Habitat Institute, Richmond, CA.

Ogden Beeman. 1992. Sediment budget study for San Francisco Bay. Prepared for the San Francisco District, U.S. Army Corps of Engineers. Ogden Beeman & Associates, Inc., Portland, OR and Ray B. Krone & Associates, Inc., Davis, CA.

Pestrong, R. 1972. San Francisco Bay tidelands. *California Geology* 25(2).

Porterfield, G, N.L. Hawley and C.A. Dunnan. 1961. Fluvial sediments transported by streams tributary to the San Francisco Bay area. U.S. Geological Survey Open-File Report.

Porterfield, G. 1980. Sediment transport of streams tributary to San Francisco, San Pablo, and Suisun Bays, California, 1909-1966. U.S. Geological Survey Water Resources Investigations 80-64.

Schoellhamer, D.H., M.A. Lionberger, B.E. Jaffe, N.K. Ganju, S.A. Wright and G.G. Shellenbarger. 2005. Bay sediment budget: Sediment Accounting 101. Pages 59-63 in: *Pulse of the Estuary 2005*, San Francisco Estuary Institute, Oakland, CA.

Schoellhamer, D.H., G.G. Shellenbarger and N.K. Ganju. 2003. Sediment dynamics drive contaminant dynamics. Pages 21-26 in: *Pulse of the Estuary 2003*, San Francisco Estuary Institute, Oakland, CA.

Schultz, E.A. 1965. San Francisco Bay dredge spoil disposal. Presentation to the Committee on Tidal Hydraulics 53rd meeting in San Francisco, May 1965.

Segar, D.A. 1990. Turbidity and suspended sediments at the Alcatraz, California, dumpsite. Pages 92-101 in: Simenstad, C.A. (ed.), *Effects of Dredging on Anadromous Pacific Coast Fishes*. Workshop Proceedings, Seattle, September 8-9, 1988. Washington Sea Grant Program, University of Washington, Seattle, WA.

Simenstad, C.A. 1990. Summary and conclusions from workshop and working discussion groups. Pages 144-152 in: Simenstad, C.A. (ed.), *Effects of Dredging on Anadromous Pacific Coast Fishes*. Workshop Proceedings, Seattle, September 8-9, 1988. Washington Sea Grant Program, University of Washington, Seattle, WA.

Smith, B.J. 1965. Sedimentation in the San Francisco Bay system. Pages 675-708 in: *Proceedings of the*

Federal Interagency Sedimentation Conference, 1963. U.S. Department of Agriculture, Miscellaneous Publication 970.

USACE. 1954. A review of sedimentation. U.S. Army Corps of Engineers. Attachment A to: DWR, 1955a, Sedimentation, Appendix G in: Report to the Water Project Authority of the State of California on the Feasibility of the Construction by the State of Barriers in the San Francisco Bay System, California Department of Water Resources, Sacramento, CA.

USACE. 1967. Report on survey of San Francisco Bay & tributaries, California, Appendix V, November 1967. U.S. Army Corps of Engineers.

Van Geen, A. and S.N. Luoma. 1999. The impact of human activities on sediments of San Francisco Bay, California: an overview. *Marine Chemistry* 64: 1-6.

Vanoni, V.A. (ed.) 1975. Sedimentation Engineering. Manuals and Reports on Engineering Practice No. 54, American Society of Civil Engineers, New York.

Wheelock, K. 2003. Pulsed river flooding effects on sediment deposition in Breton Sound Estuary, Louisiana. MS thesis, Louisiana State University.

Wright, S.A. and D.H. Schoellhamer. 2004. Trends in the sediment yield of the Sacramento River, California, 1957–2001. *San Francisco Estuary and Watershed Science* 2(2): article 2.  
<http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art2/>.

Wright, S.A. and D.H. Schoellhamer. 2005. Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento–San Joaquin River Delta. *Water Resources Research* 41, W09428, doi:10.1029/2004WR003753.