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Comparison of sediment supply to San Francisco Bay from watersheds draining the Bay Area and the Central Valley of California

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ABSTRACT

Quantifying suspended sediment loads is important for managing the world's estuaries in the context of navigation, pollutant transport, wetland restoration, and coastal erosion. To address these needs, a comprehensive analysis was completed on sediment supply to San Francisco Bay from fluvial sources. Suspended sediment, optical backscatter, velocity data near the head of the estuary, and discharge data obtained from the output of a water balance model were used to generate continuous suspended sediment concentration records and compute loads to the Bay from the large Central Valley watershed. Sediment loads from small tributary watersheds around the Bay were determined using 235 station-years of suspended sediment data from 38 watershed locations, regression analysis, and simple modeling. Over 16 years, net annual suspended sediment load to the head of the estuary from its 154,000 km^2 Central Valley watershed varied from 0.13 to 2.58 (mean = 0.89) million metric t of suspended sediment, or an average yield of 11 metric t/km^2/yr. Small tributaries, totaling 8145 km^2, in the nine-county Bay Area discharged between 0.081 and 4.27 (mean = 1.39) million metric t with a mean yield of 212 metric t/km^2/yr. The results indicate that the hundreds of urbanized and tectonically active tributaries adjacent to the Bay, which together account for just 5% of the total watershed area draining to the Bay and provide just 7% of the annual average fluvial flow, supply 61% of the suspended sediment. The small tributary loads are more variable (53-fold between years compared to 21-fold for the inland Central Valley rivers) and dominated fluvial sediment supply to the Bay during 10 out of 16 yr. If San Francisco Bay is typical of other estuaries in active tectonic or climatically variable coastal regimes, managers responsible for water quality, dredging and reusing sediment accumulating in shipping channels, or restoring wetlands in the world's estuaries may need to more carefully account for proximal small urbanized watersheds that may dominate sediment supply.

1. Introduction

The transport of sediment from land to many of the world's most populous estuaries and adjacent coasts often forms the basis for computations of loads of other water quality constituents and is important for resource management decisions (Long Island Sound: Bokuniewicz et al., 1976; Choptank River Estuary: Yabro et al., 1983; Chesapeake Bay: Hobbs et al., 1992; Brisbane River Estuary and Moreton Bay: Eyre et al., 1998; Eyre and McKee, 2002; Mississippi and Gulf of Mexico: Turner et al., 2007; Southern California Bight: Warrick and Farnsworth, 2009, East China Sea: Deng et al., 2006; Southern San Francisco Bay: Shellenbarger et al., 2013–this issue). However, sediment load remains extremely difficult to estimate. Difficulties can include a lack of, or low-quality, suspended sediment data, a lack of bed-load transport data, a lack of reliable water discharge information in key basin locations, unknown sediment trapping characteristics of upland dams and lowland basin components (such as flood control channels and sediment catch basins), sporadic or absent records of sediment removal, and non-stationary natural or human perturbations (Walling, 2006; Warrick and Rubin, 2007). Accurate sediment load computations are also affected by highly variable climate and stochastic heterogeneous sediment erosion processes in active tectonic regimes (Milliman and Syvitski, 1992; Inman and Jenkins, 1999) and can be exacerbated by occasional wildfires (Warrick and Rubin, 2007). The Mediterranean climate, fire regime, ongoing urbanization, and active tectonic processes in the San Francisco Bay area provide an array of challenges associated with quantifying temporally and spatially explicit sediment loads to a highly human-impacted coastal marine system.

Estimates of suspended sediment loads entering San Francisco Bay have been presented by a number of researchers (e.g., Gilbert, 1917; Krone, 1979; Porterfield, 1980; McKee et al., 2003; McKee et al., 2006;

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Lewicki and McKee, 2010). Each author chose from a variety of available methods of quantification; for example, total basin erosion, yield, and bay deposition (Gilbert, 1917) or sediment rating curve methods using either daily or annual discharge (Krone, 1979; Porterfield, 1980; McKee et al., 2003). Over the time since these estimates were made, watershed conditions have changed, and loading from the Sacramento–San Joaquin watershed has decreased (Krone, 1996; Wright and Schoellhamer, 2004; Ganju et al., 2008; Schoellhamer, 2011). The supply of sediment from smaller tributaries may now be larger than initially estimated and knowledge about this sediment source may be increasingly important for management decisions (Downing-Kunz and Schoellhamer, 2013-this issue). McKee et al. (2006) presented new estimates of suspended sediment loads to the Bay from the large Sacramento–San Joaquin Rivers via the Delta for water year (WY) 1995–2003, but these can be now updated by incorporating more recent data into the computations. In addition, Lewicki and McKee (2010) presented a new methodology for mean annual small tributary load estimation but did not address the issue of inter-annual climatic variability.

Therefore, the objective of this study was to update methods and improve sediment load estimates for both the larger Sacramento–San Joaquin Rivers (McKee et al., 2006) and the smaller urbanized tributaries (Lewicki and McKee, 2010). Here, we provide more consistent treatment of climatic variation and non-stationarity and present a more spatially explicit analysis for direct use by those wishing to model and manage Bay sedimentation and pollution processes. We show that a majority of suspended sediment load to the Bay is contributed by the small tributaries draining the nine Bay Area counties, a conclusion that may be counterintuitive to many managers, since small tributaries only account for 5% of the Bay's total watershed area upstream of the mouth of the Bay at the Golden Gate Bridge. We also suggest that the methods presented here could be applied to coastal systems in other parts of the world. In this contribution, we focus on the computation of fine suspended sediment load for the recent period (about 80% of which is $<$62.5 μm; silt and clay sized fractions). Although knowledge of coarser sediment load is desirable to managers, the lack of bed load data prevents the computation of this portion of the sediment load and remains a weakness in this study. Even though bed load is estimated to be $<$10% of the total load (Porterfield, 1980; Schoellhamer et al., 2012), we will discuss the challenges presented by the lack of bed load data and practical solutions.

2. Methods

2.1. Regional setting

The San Francisco Bay estuary landward of the Golden Gate Bridge receives discharge and sediment loads from about 483 tributary watersheds comprising an area of 162,145 km^2 (Fig. 1). The Sacramento and San Joaquin Rivers together form a large inverted delta at the northeastern extremity of the river-dominated northern estuary and together drain 154,000 km^2 of California's Central Valley. Here, we treat the Sacramento and San Joaquin Rivers and all the other tributary watersheds that drain to the Bay from the Central Valley as one large watershed. A further 8145 km^2 (5% of the total Golden Gate watershed) is associated with the remaining 482 smaller watersheds (hereafter referred to as the "small tributaries") of the nine urbanized counties that directly fringe the Bay (Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco). The geology of the Central Valley includes highly indurated granitic, meta-sedimentary, and meta-volcanic rocks in the western-facing slopes of the Sierra Nevada Mountains and more friable marine sedimentary and meta-sedimentary rocks in the eastern-facing slopes of the coastal ranges. The small tributaries of the Bay Area are dominated by the more erodible marine sedimentary and meta-sedimentary rocks (see geological map of California: CGS, 2006). Both the Sierra Nevada and the coast range mountains are subject to periodic and often destructive wildfires that lead to temporary but large increases in the erodible sediment pool (Moody and Martin, 2009). Land use in the free-flowing areas of the Sacramento–San Joaquin watershed is dominated by agriculture with a number of large urban centers. Land use in the small tributaries of the Bay Area is approximately 50% urbanized, housing a total population of 7.151 million (Census, 2010). Seasonal discharge from the Sacramento–San Joaquin watershed is influenced by snow in the Sierra Nevada Mountain Range and storage behind dams (48% of the drainage area is upstream from dams that drain a minimum area of 100 miles^2 (260 km^2), Minear, 2010). Peak annual mean monthly discharge occurs in March (Table 1) once significant accumulations of snow are able to melt during warm spring temperatures, enhanced by less frequent warm spring rain storms, and, in some years, when dams discharge. Mean annual unit discharge from the combined Sacramento and San Joaquin Rivers for WY 1971–2010 was 148.4 mm with about 85% occurring from November to May inclusively (Table 1). In contrast, unit discharge for the same period was 1.6-fold greater in response to rainfall in the steeper, smaller, and more impervious urbanized small tributaries directly adjacent to the Bay. In these watersheds, mean peak discharge occurs in February each year and a mean of 93% of the discharge occurs from October to April almost completely in relation to rainfall (Table 1).

2.2. Sacramento–San Joaquin watershed sediment loads

2.2.1. Mallard Island sampling location

Sampling for computation of suspended sediment loads to the Bay from the Sacramento–San Joaquin watershed was conducted at Mallard Island downstream from the Sacramento/San Joaquin River Delta from WY 1995–2010 (Fig. 1). The Mallard Island cross section, hereafter assumed to be the delivery point to the Bay, was selected because of a long-term monitoring effort by the California Department of Water Resources (DWR) (California Data Exchange Center station code MAL) and the United States Geological Survey (USGS) (station number 11185185). However, tidal processes in this cross section do disperse a mean of 20% of the advected sediment back upstream, mostly during non-flood conditions; an amount that is within the error bounds of the computations (McKee et al., 2006). The channel depth at the Mallard Island DWR pier (50 m out into the channel from Mallard Island) is 7.6 m. Elsewhere in the 940 m wide cross section, the shipping channel has a maximum depth of about 17 m and the diurnal tidal range (mean lower low water to mean higher high water) is 1.25 m (DWR, unpublished data). Mallard Island is 8 km downstream of the confluence of the Sacramento and San Joaquin Rivers and is representative of the combined Sacramento and San Joaquin River watershed (McKee et al., 2006). The Delta upstream of the sampling location is complex with many sloughs, modified channels, reclaimed islands, and complex water and sediment circulation processes (Wright and Schoellhamer, 2005; David et al., 2009). As a result, the discharge from upstream sources is well mixed as it passes Mallard Island.

2.2.2. Mallard Island hydrology data to support load computations

Daily discharge data for the Delta is available from DWR for the period WY 1956 to present. Given that Mallard Island is tidally influenced, the net mean daily discharge is computed by DWR using a water balance model, called "Dayflow" (IEP, 2012a). One of the output parameters, "Delta outflow", is a daily estimate of total discharge to San Francisco Bay through the cross-section at Mallard Island. The water balance computational scheme does not include accounting parameters for variation in discharge that is caused by the spring–neap tidal cycle. However, given that floods pass through this very large river system over a period of weeks, this limitation has little influence on suspended sediment load computations (McKee et al., 2006). The May 18th, 2011 data release from DWR (IEP, 2012b) was used in our computations.

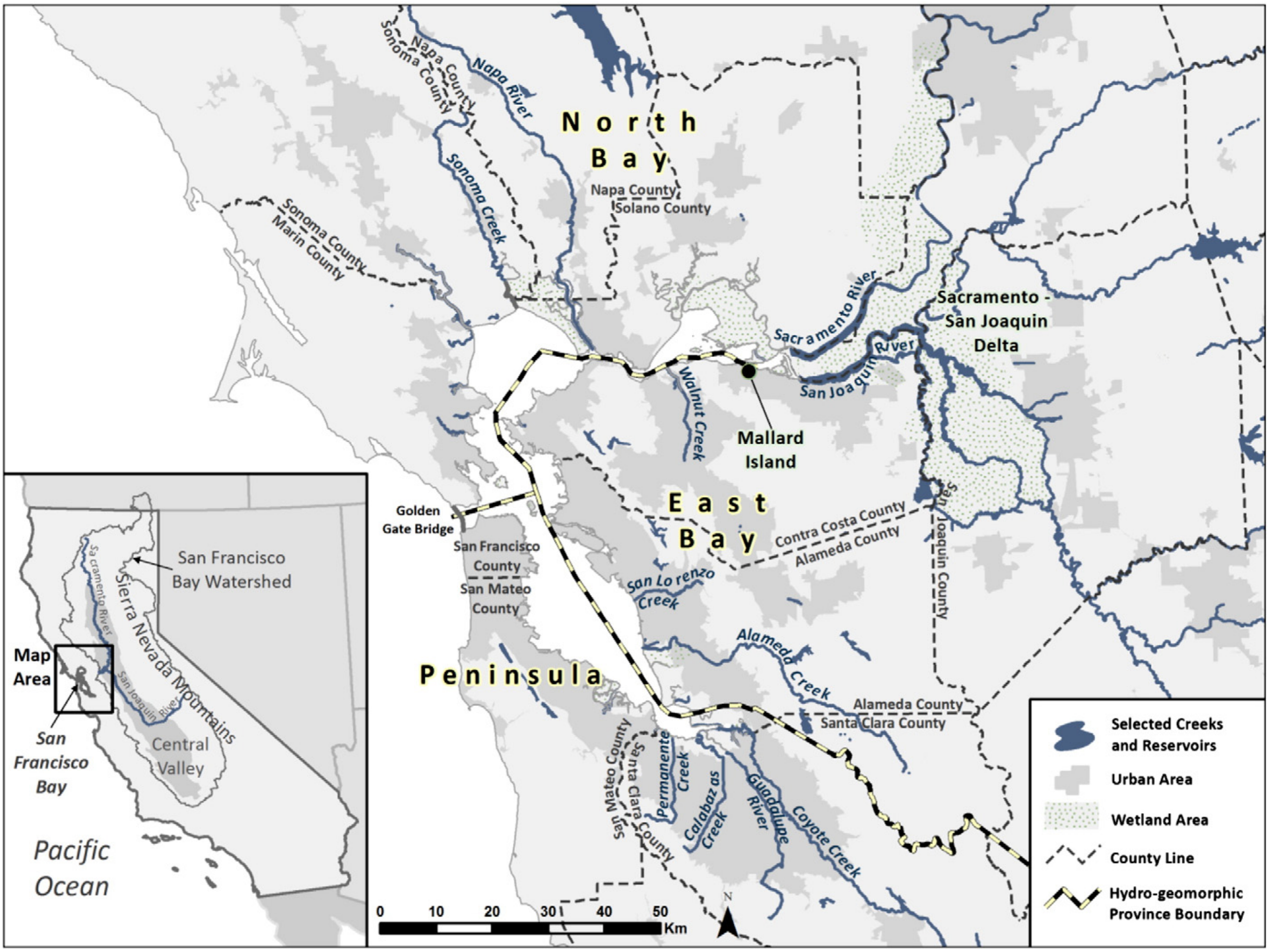

Fig. 1. Study area of the "Golden Gate" watershed draining to the Pacific Ocean via San Francisco Bay.

2.2.3. Mallard Island turbidity and suspended sediment concentration data

Turbidity was measured and recorded at a 15-minute sampling interval at a USGS-operated gauging station located at the end of the pier at Mallard Island (station number 11185185) from February 9, 1994 to present. Turbidity was measured at two depths (2 m above the channel bed and 1 m below the water surface), post-processed to remove errors associated with biological fouling, and converted to suspended sediment concentration (SSC) data using correlation and discrete depth specific analyses for SSC (e.g. Buchanan and Morgan, 2011). During much of the period of interest (October 1st, 1994–September 30th, 2010), datasets were reasonably complete. Only 15% of data (910 days) were lost or unusable due to equipment malfunction, biological fouling, and vandalism. Reliability of the instrumentation and field practices have steadily improved, such that currently <5% of data are lost (Buchanan and Morgan, 2011). Data gaps were filled using linear interpolation. Most interpolated data occurred during drier discharge periods, with little impact on the accuracy of the computed loads at the annual scale (McKee et al., 2006; David et al., 2009).

2.2.4. Mallard Island load computation method

Computations of mass loads through a tidally influenced cross section are the sum of (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). As described previously (McKee et al., 2006), data limitations for the Mallard Island cross section impede our ability to calculate the sediment mass transport associated with many of the terms with the exception of advection and dispersion (number 1 and 2 above). Advective loads were calculated for each day of the 16-year record by combining delta outflow from the Dayflow model (million cubic meters (Mm^3)) with mean 24-h surface SSC (mg/L equivalent to metric t/Mm^3). Advective loads were then "adjusted" for dispersive flux (most often in the upstream direction) using a more limited data set following the methods described by McKee et al.(2006). With the exception of one day in 1994, when there was a net load upstream, the maximum adjustment was −82% under a dry summer discharge condition of 33.8 m^3/s. However, during high discharges, dispersive load is greatly outweighed by advective load; a minimum adjustment of −0.07% at a discharge of 16,061 m^3/s was made on January 3rd, 1997. Given that the majority of loads occurred under high discharge conditions, the mean 16-year adjustment was −20% (coincidentally the same adjustment as reported by McKee et al. (2006) using the first nine years of data only).

2.2.5. Mallard Island load computation method error bounds

To characterize computational uncertainty, estimates of overall root-mean-square (RMS) error associated with load computations were developed by McKee et al. (2006) accounting for the error associated with: 1) the variability of up to 96 turbidity measurements in a 24-hour period, 2) discharge computations and resulting data, 3) SSC laboratory analysis, 4) conversion of turbidity to SSC using regression, and 5) lateral and vertical variability in water column SSC. The computed RMS error was 32% and remains valid for load summations for one year or less (McKee et al., 2006) and for this present work. The long term decadal-scale mean loads computed from the annual loads should be more accurate (e.g. Toor et al., 2008).

2.3. Nine-county Bay Area urbanized small tributary loads

2.3.1. Hydrology and SSC data to support small tributary load computations

Within the nine-county Bay Area, the USGS and collaborators have been responsible for collecting suspended sediment data at 38 small tributary gauging locations ranging in size from 0.70 km^2 to 1639 km^2 (Table 2). These data were downloaded using the USGS website web query tool (e.g., USGS, 2012a) augmented, in a few cases, by published sources (Porterfield, 1972; Brown and Jackson, 1973; Brown and Jackson, 1974; Porterfield, 1980). Suspended sediment data span a period from WY 1957 to 2010 for a total of 235 station years. These 38 sediment gauges together drain an area of 4156 km^2 or about 51% of the area of interest. An additional eight locations with discharge data only were also included in this analysis to estimate discharge in ungauged tributaries (Table 2). Some watersheds and some time periods were specifically excluded because of known trends (see below for details and the discussion section for more on trends and non-stationarity).

Our computational scheme was based on the assumption that small dams and on-channel stock ponds do not impede sediment transport. This assumption remains a weakness for smaller dams given that some amount of sediment must be stored (Willis and Griggs, 2003). Some of the larger gauged small tributary watersheds in the Bay Area have one or more larger dams capturing 10% or more of each individual watershed area and that in aggregate capture a watershed area of 1600 km^2. A majority of this impoundment is located in the San Lorenzo Creek, Alameda Creek, Coyote Creek, Guadalupe River, San Francisquito Creek, and Napa River watersheds, all of which have been or are currently gauged for water and suspended sediment discharge. Because the computations were based on discharge data — not watershed area, the sediment trapping effects of these larger impoundments are taken into account in our computations. In a few other cases described below, we assumed 100% trapping efficiency for the area upstream of dams.

2.3.2. Suspended sediment load computations for small tributaries

In all computations, we defined the delivery point to the Bay as the head of tide. Depositional processes that occur between the head of tide and the open Bay are not considered here but are discussed elsewhere (Downing-Kunz and Schoellhamer, 2013–this issue). Three methods were used to compute loads for small tributaries in the nine-county Bay Area using class-specific methods for three classes of watersheds: 1) those with empirical suspended sediment field data, 2) those without empirical field data but dominated by non-urban land use, and 3) those without empirical field data dominated by urban land use. This computational scheme was based on a previous study by Lewicki and McKee (2010), who found that the suspended sediment data set was insufficient to statistically relate spatial variation in sediment loads in Bay Area small tributary watersheds to urban land use influences. Similarly, watershed area, non-urban land uses, construction/development, geology, and elevation did not explain enough of the variability to allow for the development of a multiple parameter regression model (Lewicki and McKee, 2010). Instead, they found that the correlation coefficient between annual suspended sediment load and annual peak discharge was greater than the correlation coefficient between annual suspended sediment load and annual total discharge, daily average discharge, or any other independent variable tested for the less urbanized agriculturally dominated small tributary watersheds. This may be due to several factors: 1. Suspended loads are less than the theoretical transport capacity (Porterfield, 1972; Walling, 1977), 2. the annually recurrent dry period (May to September of most years) returns the stream discharge and sediment transport regime to virtually the same condition by the beginning of each subsequent wet season (Krone, 1979), and 3. because USGS sampling programs have applied the techniques of Porterfield (1972), in which suspended sediment discharge is computed as the product of discharge and the discharge-dependent sediment concentration based on instantaneous data for a limited number of "representative" storms each year, rather than measured continuously or using a surrogate, such as turbidity.

Based on previous work of Rantz (1971), and the recommendations of Lewicki and McKee (2010), the USGS water discharge and suspended sediment data were subdivided into three distinct hydrogeomorphic provinces (defined by climate and geology) to improve the correlation between the instantaneous peak discharge for a given year and suspended sediment load. These were: East Bay (Contra Costa and Alameda Counties), North Bay (Marin, Sonoma, Napa, and Solano Counties), and San Francisco Peninsula/South Bay (South San Francisco, San Mateo, and Santa Clara Counties) (Fig. 1). When instantaneous peak discharge data were not available, WY specific regression relationships distinctive to each hydrogeomorphic province were used to estimate instantaneous

Table 1
Monthly and average annual discharge characteristics for the Sacramento and San Joaquin Rivers (larger rivers) compared to the smaller coastal tributaries that drain the urbanized nine-county Bay Area.

Month	[1]Larger rivers (mm)	Cumulative (%)	[2]Nine-county small tributaries (mm)	Cumulative (%)
October	4.0	2.7	2.0	0.8
November	6.6	7.1	7.3	3.9
December	13.8	16.4	27.1	15.4
January	24.1	32.7	54.1	38.2
February	25.3	49.7	61.1	64.0
March	27.1	68.0	50.3	85.2
April	16.7	79.2	19.4	93.4
May	12.0	87.3	7.0	96.3
June	7.0	92.1	3.2	97.6
July	4.5	95.1	2.1	98.6
August	3.3	97.3	1.8	99.3
September	4.0	100.0	1.6	100.0
[3]Water year total	148.4		237.0	
[4]1971–2010 monthly runoff				
Minimum	0.83		0.60	
Maximum	131		364	
Mean	12		20	
Standard deviation	18		44	
Coefficient of variation	145		220	

[1] Delta outflow from the Dayflow model (IEP, 2012a). Based on the total watershed area including area upstream of dams.
[2] Eight-station index (USGS discharge gauging stations: Novato Creek at Novato (11459500), Napa River near Napa (11458000), San Ramon Creek at San Ramon (11182500), Dry Creek at Union City (11180500), Alameda Creek at Niles (11179000), Guadalupe River at San Jose/Hwy 101 (11169000/11169025), San Francisquito Creek at Stanford University (11164500), and Saratoga Creek at Saratoga (11169500)). Based on the total watershed area including area upstream of dams.
[3] A water year runs October 1st to September 30th with the year designated by the end date.
[4] A 40 yr averaging period accounts for the extreme climatic variability observed in the arid southwest United States.

Table 2
Available United States Geological Survey (USGS) stream discharge and suspended sediment data records used in suspended sediment computations for the nine counties adjacent to San Francisco Bay (all dates refer to the water year ending September 30th). Note, there was less suspended sediment data collected during the 1980s and 1990s.

USGS station number	USGS station name	Area (km^2)	Stream flow records	Suspended sediment records
11185185	Suisun Bay at Mallard Island	154,000	–	1995–2010
11179000	Alameda Ck. at Niles	1639	1957–2010	1957–1973, 2000–2010
11177000	Arroyo De La Laguna near Pleasanton	1049	1970–1983, 1988–2003	2000–2003
11176900	Arroyo De La Laguna at Verona	1044	2004–2010	2007–2010
11172175	Coyote Ck. above Highway 237 at Milpitas	826	1999–2010	2004–2007, 2009, 2010
11458000	Napa R. near Napa	565	1960–2010	1977, 1978, 1981
11169025	Guadalupe R. above Highway 101 at San Jose	414	2003–2010	2003–2010
11176500	Arroyo Valle near Livermore	381	1958–1967	1963, 1965–1967
11169000	Guadalupe R. at San Jose	378	1956–2003	–
11173575	Alameda Ck. below Welch Ck. near Sunol	375	2000–2010	2000–2003, 2007–2010
11176400	Arroyo Valle below Lang Canyon near Livermore	337	1964–2010	1974–1977, 1979
11169800	Coyote Ck. near Gilroy	282	1961–1982, 2005–2010	1962–1976
11183600	Walnut Ck. at Concord	221	1969–1992, 1997	1969, 1970
11460600	Lagunitas Ck. Nr. Pt. Reyes Station	212	1975–2010	1990
11183500	Walnut Ck. at Walnut Creek	205	1958–1968	1966–1968
11456000	Napa River near Saint Helena	204	1956–1996, 2010–2010	1961, 1962
11173200	Arroyo Hondo near San Jose	200	1969–1981, 1995–2010	–
11458500	Sonoma Creek at Boyes Hot Spring	162	1956–1962	1956–1962
11167800	Guadalupe R. above Almaden Expressway at San Jose	160	2004–2010	2008–2010
11458500	Sonoma Creek at Agua Caliente	151	1963–1981, 2002–2010	–
11162500	Pescadero Ck. near Pescadero	119	1956–2010	1980
11181040	San Lorenzo Ck. at San Lorenzo	116	1968–1978, 1988–2010	1990–1993, 2009, 2010
11164500	San Francisquito Ck. at Stanford	97.0	1956–2010	1962–1969
11460800	Walker Ck. near Tomales	96.1	1960–1984	1971
11460400	Lagunitas Ck. at Samuel P. Taylor State Park	89.0	1983–2010	2004–2006
11460750	Walker Ck. near Marshall	81.0	1984–2010	2004–2006
11166550	Stevens Ck. at Mountain View	63.5	2006–2009	–
11153900	Uvas Ck. above Uvas Reservoir near Morgan Hill	54.4	1962–1982	1962–1976
11460000	Corte Madera Ck. near Ross	47.0	1960–1993, 1997, 2010	1978–1980, 1984, 2010
11180825	San Lorenzo Ck. above Don Castro Reservoir near Castro Valley	46.6	1981–1991, 1993, 1994, 1998–2010	1998–1989, 1992, 1994, 1998–2003
11459500	Novato Ck. at Novato	45.6	1956–2010	–
11162720	Colma Ck. at South San Francisco	28.0	1964–1994, 1996	1966–1976
11180900	Crow Creek near Hayward	27.2	1998–2010	2000–2003
11153470	Llagas Ck. above Chesbro Reservoir Nr. Morgan Hill	24.9	1972–1982, 2004–2010	1972–1978
11180500	Dry Ck. at Union City	24.3	1959–2010	–
11169500	Saratoga Ck. at Saratoga	23.9	1956–2010	–
11460170	Pine Ck. at Bolinas	20.0	1968–1970	1968–1970
11181390	Wildcat Ck. at Vale Road at Richmond	20.0	1976–1997	1978–1980
11166000	Matadero Ck. at Palo Alto	18.8	1956–2010	–
11180960	Cull Ck. above Cull Ck. Reservoir near Castro Valley	15.0	1978–2010	1979–1989, 1992, 1995–2003
11169616	Calabazas Ck. at Rainbow Drive near Cupertino	10.3	1974–1978	1974–1977
11166575	Permanente Ck. near Monte Vista	10.0	1985–1987	1985–1987
11166578	West Fork Permanente Ck. near Monte Vista	8.00	1985, 1986	1985, 1986
11182500	San Ramon Ck. at San Ramon	5.89	1956–2010	–
11172365	Zone 6 Line B at Warm Springs Boulevard at Fremont	2.15	2000–2002	2000–2002
11162722	Spruce Branch at South San Francisco	1.81	1966–1969	1966–1969
11169580	Calabazas Cr. Tributary at Mount Eden Road near Saratoga	0.958	1973–1978	1973–1977
11169600	Prospect Creek at Saratoga Golf Course near Saratoga	0.699	1973–1975	1973–1975

peak discharge in each watershed. Instantaneous peak discharge was related to watershed area for each WY, for each hydrogeomorphic province by the relationship:

$$Q_p = cA^x \quad (1)$$

where Q_p represents instantaneous peak discharge, A is the area of the watershed upstream of the gauge location, and c and x represent the WY specific conversion of rainfall into discharge in relation to mean regional physiographic and climatic conditions. The resulting highly significant regressions based on empirical data from between 4 and 14 watersheds depending on the year and province had correlation coefficients ranging between $r^2 = 0.69$–0.99 with a median r^2 of 0.85.

Suspended sediment loads from watersheds of mostly non-urban land use were computed using a sediment discharge rating equation (Leopold and Maddock, 1953) in the form:

$$Q_s = aQ_p^b \quad (2)$$

where Q_s represents sediment load, Q_p represents instantaneous peak discharge, a is a function of the sediment supply, and b represents the erosive power of the water discharge. These parameters are also dependent on land use, climate, hydraulics, and particle-size distribution. Both a and b are constants unique to each watershed that scale water discharge (units volume per unit time) to suspended sediment loads (units mass per unit time).

As described above, the 482 watersheds had differing datasets available for analysis, and were separated into classes for analysis. The first watershed class, for which empirical data were available, included 12 watersheds covering 56% of the nine-county area of interest. For these, empirical field observations made by the USGS spanning at least five WYs were used to generate watershed-specific regression relationships (Table 3). For WYs between 1995 and 2010 for which published USGS records of annual sediment load were not available, but for which instantaneous peak discharge data were available, these regression relationships were applied to estimate WY specific annual suspended sediment load. In one additional watershed, locally called Zone 6 Line B, with an area of just 2.15 km^2, where empirical data were available for just three WYs, and where elevated sediment loads were likely in

Table 3
Suspended sediment computation methods and resulting suspended sediment loads for 16 water years spanning 1995–2010.

Watershed name	Province	Watershed class	Gauged area (km^2)	Total watershed area (km^2)	Area upstream from major reservoirs (km^2)	Flow estimation method			Sediment area estimation method			Average annual suspended sediment		
						Empirical field measured	Water year specific regional regressions	Local regression	Empirical field measured	Watersheds specific regression	Regional regression	Water years 1995–2010 (metric t)	[1](metric t/km^2/yr)	[2](metric t/km^2/yr)
Sacramento–San Joaquin Rivers	Central Valley	1	154,000	154,000	73,920							892,000	5.8	11
Alameda Creek	East Bay	1	1639	1664	737	1995–2010			2000–2010	1995–1999		112,346	68	121
Walnut Creek		1	221 \205[3]	321	3.5		1995–2010			1995–2010		74,501	232	235
San Leandro Creek		2		128	107		1995–2010				1995–2010	5811	45	278
San Lorenzo Creek		1	116	125	62	1995–2010			2009, 2010	1995–2008		16,895	135	266
San Pablo Creek		2		106	83		1995–2010				1995–2010	6176	58	269
Pinole Creek		2		38.1	0		1995–2010				1995–2010	8946	235	235
Mount Diablo Creek		2		32.0	0		1995–2010				1995–2010	7877	246	246
Wildcat Creek		2		25.7	0		1995–2010				1995–2010	6703	261	261
Dry Creek		2	24.3	24.3	0	1995–2010					1995–2010	3445	142	142
Zone 6 Line B		1	2.15	2.15	0	2000–2002	1995–1999; 2003–2010		2000–2002	1995–1999; 2003–2010: measured WY 2000 load scaled to annual flow		58,340	27,100	27,100
Napa River	North Bay	1	565	738	215	1995–2010				1995–2010		310,928	422	595
Sonoma Creek		1	151	241	0	2002–2010		Napa R. at Napa 1995–2001		1995–2010		204,516	847	847
Suisun Creek		2		134	0		1995–2010				1995–2010	30,051	224	224
Petaluma River		2		122	0		1995–2010				1995–2010	26,059	213	213
Novato Creek		2	45.6	96.2	22.4	1995–2010					1995–2010	7366	77	100
San Antonio Creek		2		80.1	0		1995–2010				1995–2010	13,417	168	168
Corte Madera Creek		1	47.0	48.2	5.7	1997, 2010	1995, 1996, 1998–2009		1997, 2010	1995, 1996, 1998–2009		10,461	217	246
Carneros Creek		2		22.2	0		1995–2010				1995–2010	1989	90	90
Mill Creek		2		12.1	0		1995–2010				1995–2010	843	70	70
Coyote Creek	Peninsula/ South Bay	1	826	833	503	1999–2010	1995–1998		2004–2007, 2009, 2010	1995–2003, 2008		8230	9.9	25
Guadalupe River		1	414	446	178	1995–2010			2003–2010	1995–2002		7975	18	30
San Francisquito Creek		1	97.0	118	38	1995–2010				1995–2010		40,081	340	504
San Mateo Creek		2		86	74		1995–2010				1995–2010	851	10	71
Stevens Creek		2	63.5	79.2	45.3	2006–2009		Matadero 1995–2005; 2010			1995–2010	2582	33	76
Calabazas Creek		1		52.9	0.0		1995–2010			1995–2010		4832	91	91

Table 3 (*continued*)

Watershed name	Province	Watershed class	Gauged area (km^2)	Total watershed area (km^2)	Area upstream from major reservoirs (km^2)	Flow estimation method			Sediment area estimation method			Average annual suspended sediment		
						Empirical field measured	Water year specific regional regressions	Local regression	Empirical field measured	Watersheds specific regression	Regional regression	Water years 1995–2010		
												(metric t)	[1](metric t/km^2/yr)	[2](metric t/km^2/yr)
Permanente Creek		1	10\8[3]	45.4	0.0		1995–2010			1995–2010		4022	89	89
Colma Creek		1	28.0	40.8	0.0	1996	1995; 1997–2010			1995–2010		19,421	476	476
Matadero Creek		2	18.8	31.0	0.0	1995–2010					1995–2010	2871	93	93

Note, all data are provided to three significant figures (where possible) to allow data post-processing by other researchers and do not represent a claim of relative accuracy or precision. Class 1 watersheds have empirical suspended sediment field data. Class 2 watersheds are those without empirical field data but dominated by non-urban land use.

[1] Caculated based on total watershed area.

[2] Caculated based on "free flowing" watershed area downstream from major dams.

[3] The gauge location shifted during the period of record causing a slight change in gauged watershed area.

response to earthflows exacerbated by recent urban development, loads were computed for non-measured WYs by scaling the WY 2000 load to annual instantaneous peak discharge. We did not include this special case in the other, more general relationship, for the East Bay province.

The second class of watersheds (those without empirical suspended sediment field data but dominated by non-urban land use), included 15 watersheds comprising a watershed area of 1143 km^2 (14% of the Bay Area watershed area). For these, loads were computed by combining regional regression relationships specific to each hydrogeomorphic province with measured instantaneous peak discharge or instantaneous peak discharge estimated using either a local regression with an adjacent watershed where it was found to be robust (Sonoma and Stevens Creeks, Table 3) or WY specific regional regression developed for each province (Table 3). In five watersheds (Walnut Creek, San Leandro Creek, San Pablo Creek, San Mateo Creek, Corte Madera Creek), the area upstream from the dams was excluded from computations. In Stevens Creek and Novato Creek, available empirical discharge measurements already accounted for water management in storage dams. Thus, including both classes, a total of 70% of the watershed area of interest draining the nine counties around the Bay was either empirically measured or estimated by regression based on empirically measured data.

The third class of watersheds comprised the lowland, mostly urbanized Bay watersheds that fringe the Bay, in which few empirical field measurements have been made by the USGS or any other entity to-date (Lewicki and McKee, 2010). As such, the discharge-based regression methods described above could not be applied to ungauged small tributaries in the Bay Area where land use is dominantly urban. To estimate the sediment loads contributed by lowland small non-urban or urbanized land use in the Bay Area small tributaries comprising the final 30% of the watershed area draining to the Bay from the nine counties, the land use based estimation method described by Donigian and Love (2003) was applied based on data extracted from published literature. This approach is part of integrated discharge and sediment prediction models such as Hydrologic Simulation Program-Fortran (HSPF) (EPA, 2008).

To apply the method, a watershed boundary layer was needed in urban areas where the engineered drainage system may not follow topographic relief. Such a boundary layer was available for the lowland urbanized portions of Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco counties (SFEI, 2012). Such a boundary layer was not available for the northern counties of Marin, Sonoma, Napa, and Solano; watershed boundaries were generated for these watersheds using a 30-m spatial resolution USGS National Elevation Data (NED) digital elevation model (DEM) (USGS, 2012b). Land use data were obtained from the Association of Bay Area Governments (ABAG, 2000) and classified into five main land use categories. The watershed boundary and land use data sets were overlaid in ArcGIS (ESRI) and then watershed-specific land use statistics were determined. Typical erosion rates from Donigian and Love (2003) and the HSPF manual (EPA, 2008) (Table 4) were then applied to the urbanized watershed areas and land uses to compute gross sediment erosion. A sediment delivery ratio was used to estimate the fraction of gross sediment erosion occurring in a land use segment that reaches the channel ("edge of stream" inputs). We used the method developed by the United States Department of Agriculture (USDA) (NRCS, 1983):

$$DR = 0.417762A^{-0.134958} - 0.127097 \tag{3}$$

where DR is the delivery ratio (decimal fraction), which decreases as watershed size increases, and A is the watershed area (note that USDA formula is in US units [$miles^2$]). We assumed that all sediments delivered to a channel were transported to the head of tide of the tidal reaches of small tributaries (perhaps a reasonable assumption within urban drainage systems where fine sediments are conveyed efficiently by high velocities). Suspended sediment load to the Bay for a given land use in a given watershed was computed as the product of the sediment yield from Table 4 and the area of each land use in the watershed, summed for all the land uses to the total watershed area. The total gross sediment erosion was then scaled by the delivery ratio (DR) specific for each tributary to compute mean annual suspended sediment load. To estimate the WY specific load for each of the 16 WYs, a ratio multiplier (derived from the 13 watersheds which had empirical observations in class 1) was applied to the mean annual load. Climatic variation of sediment loads is likely less in dominantly urban small tributary watersheds relative to larger agriculturally-dominated small tributary watersheds due to more consistent erosion sources in urban systems. In contrast, larger watersheds can include a greater proportion of sediment sourced from landslides, gully erosion, bank erosion, and bed incision that are more stochastic in nature. However, given the lack of long-term empirical observations in Bay Area urbanized small tributary watersheds, estimates of climatic variability derived from larger

Table 4
Sediment production rates estimated for selected land use classes based on published information compiled by Donigian and Love (2003) and EPA (2008).

	Natural	Agriculture	Low density urban	High density urban	Industrial
Sediment production (metric t/km^2/yr)	72	2461	450	996	1836

data-rich but less urbanized agriculturally dominated watersheds are the best possible at this time.

Construction activities in urban areas are known to generate substantial amounts of sediment within a watershed, particularly in areas with steep terrain (Chin, 2006). For the most part, the urbanized areas that fringe the Bay are no longer undergoing major construction activities. Most ongoing land use modification in these areas is conversion from industrial land use to either commercial or residential land use, both resulting in lower sediment yields. In the recent several decades, new development and construction (mostly agricultural land use conversion to urban land uses), has been taking place through urban sprawl in areas further from the Bay, mostly in larger watersheds. As such, construction impacts to sediment loads are already taken into account in the empirically-based regression methods applied in our mostly larger less urbanized agriculturally dominated watersheds as described above.

2.3.3. Error analysis for small tributary loads

In contrast to the error estimation method for Sacramento–San Joaquin watershed loads, the uncertainty for the suspended sediment loads entering the Bay from the combined area of small tributaries was more difficult to estimate. Sources of uncertainty in our computations came from three general limitations: 1) Measurement uncertainty of suspended sediment in the field, 2) the use of regression equations, and 3) uncertainty in applied land use data. For each class, we adopted what we estimate are conservative estimates.

For our first class of small tributaries that included 12 watersheds covering 56% of the nine-county area of interest, a root-mean-square (RMS) error was computed. Sources of uncertainty included: 1) the measurement of instantaneous peak discharge by the USGS using the area velocity method and a rating curve (+/−10%), 2) the development and use of WY specific regional regressions to estimate instantaneous peak discharge in the absence of empirical data specific to each province (in this case we used the median of all the correlation coefficients (r^2) of the 48 regression equations (+/−7%)), 3) the laboratory analysis of water samples collected by the USGS for SSC (+/−5%), 4) the use of rating relationships between instantaneous discharge and SSC by the USGS to compute sediment loads (+/−20%), and 5) the use of a regression estimator between instantaneous peak discharge and annual suspended sediment discharge to estimate loads for unmeasured years; in this case we used the area weighted mean of the correlation coefficients (r^2) of the 13 regression equations (+/−9.5%). The resulting RMS error was the square root of the sum of all the error terms squared or +/−25%.

For the second class of small tributaries, less urbanized agriculturally dominated watersheds that covered a further 14% of the area of interest, an additional error term associated with the development and use of regional regression equations specific to each province was applied. Based on least squares regression analysis, instantaneous peak discharge described 86% of the variability in annual suspended sediment loads for the combined data of all the Bay watersheds, thus the error bounds were set at +/−7%. Similarly, the error bounds for the East Bay and the Peninsula/South Bay provinces were +/−12.5% and +/−9.5% respectively. Taking a conservative approach, the errors associated with the use of regional regressions between instantaneous peak discharge and annual sediment loads were set at +/−12.5% resulting in a total estimated RMS error of +/−29%; not dissimilar to error bounds previously reported for suspended sediment load computations for coastal central and southern California (Inman and Jenkins, 1999: 35%; Willis and Griggs, 2003).

The uncertainty associated with the third class of small tributary urban watersheds that accounted for the remaining 30% of the area of interest was not possible to estimate by summing the error components of each step of the land use based sediment estimation method. Instead, we verified the land use based computation method outputs and determined the likely error bounds by applying it to a subset of watersheds for which the regression based methods were used to compute loads. Since the land use method was applied to watersheds which ranged in size from 0.0018 to 114 km^2 (mean = 5.4 km^2) with urban land use ranging from 0 to 100% (mean = 44%) we focused on method performance for smaller urbanized watersheds. The smallest 16 watersheds for which either real data or regression methods were used to compute sediment loads ranged from 12 to106 km^2 (mean = 51.3 km^2) and 3.1 to 75% urban land use (mean = 39%). Zone 6 Line B was excluded due to high sediment loads that have recently occurred likely because of earthflows exacerbated by recent urban development. Regardless of the cause, the sediment loads in Zone 6 Line B appear to be non-representative of other mostly stable urban watersheds in the Bay Area. Loads computed by the land use method ranged from 7% to 218% of the load computation based on measured field data and/or regression methods. The mean bias was −25% with 50% of the data ranging between 23% and 108%. The data show a trend of improving performance with increasing urbanization. This might be due to the tectonically active highly variable nature of sediment production and storage in agricultural and open-space areas within Bay Area watersheds. The performance in the most urban subset of 14 watersheds that ranged between 12.1 and 446 km^2 and 30% to 75% urban was 13% to 293% with a −11% mean bias with 50% of the watersheds between 22% and 135%. Excluding the special case of Zone 6 Line B, loads normalized to area based on our regression methods ranged between 11 and 847 metric t/km^2/yr; not dissimilar to area normalized loads based on the land use method (95% lie between 24 and 1017 metric t/km^2/yr). We conclude that land use-based load computations for individual watersheds do not have high reliability but at the sub-regional scale (province, or county), loads may be biased slightly low or quite reliable if we accept the trend of improving performance in relation to urbanization. If the preponderance of land use-based loads estimated lies somewhere between 1/2 and 2× the real load (error = −50%, +100%), then the worst case scenario for area-weighted total error bounds for the regional scale computations for all small tributaries combined would be +/−51%. This was the error bound we applied to the regional scale loads.

3. Results

Runoff volume entering San Francisco Bay from the Sacramento–San Joaquin watershed varies considerably from year-to-year in relation to normal fluctuations in climate. For example, annual runoff from the Sacramento–San Joaquin watershed for WYs 1971 to 2010 ranged from 3.055 to 79.269 km^3 (a 26-fold variation), (mean discharge = 22.855 km^3). Our study period included much of this long-term climatic variability with annual runoff ranging from 7.668 to 54.033 km^3, a variation of 7-fold with a slightly greater mean (24.682 km^3) (Table 5). In response to this variable hydrologic regime, suspended sediment loads entering the Bay from the Sacramento–San Joaquin watershed varied from 0.125 million metric tons (t) in WY 2007 to 2.58 million metric t in WY 1995, a variation of 21-fold. Over 16 yr from WYs 1995 to 2010, a total of 14.3 ± 4.165 million metric t at a mean rate of 0.892 ± 0.285 million metric t/yr (5.8 metric t/km^2/yr based on the whole watershed area or 11 metric t/km^2/yr based on the area downstream from dams) was transported into the Bay from the Sacramento–San Joaquin watershed. The WY with the greatest runoff (2006) transported 11% of the 16-year total suspended sediment load and the wettest two consecutive WYs (1997 and 1998) transported 33% of the total suspended sediment load. Relating this mean load to mean discharge characteristics, the discharge-weighted mean suspended sediment concentration in waters discharging from the Sacramento–San Joaquin watershed was 36 mg/L.

Suspended sediment loads in small tributaries varied greatly from one watershed to another mainly in relation to watershed area (Table 3). However, other factors including unit runoff (mm), land use development (mainly urban and rangeland agriculture), and geologic

Table 5
Annual discharge and suspended sediment loads entering the Bay from the Central Valley of California via the Mallard Island monitoring cross-section and from the sum of the 482 small tributaries draining directly to the Bay from the urbanized and tectonically active nine-county Bay Area.

Water year	Central Valley			Small tributaries		
	Runoff (km^3)	Load (million metric t)	Error (+/− million metric t)	Runoff (km^3)	Load (million metric t)	Error (+/− million metric t)
1995	51.559	2.58	0.826	3.93	4.27	2.18
1996	31.436	1.01	0.324	2.31	1.29	0.660
1997	42.307	2.24	0.717	2.62	2.09	1.06
1998	53.639	2.42	0.774	3.94	3.67	1.87
1999	27.805	0.842	0.270	1.43	0.678	0.346
2000	22.394	0.659	0.211	1.33	0.628	0.320
2001	8.565	0.263	0.084	0.575	0.139	0.0711
2002	11.303	0.309	0.099	1.24	0.394	0.201
2003	17.330	0.546	0.175	1.80	2.30	1.18
2004	18.577	0.640	0.205	1.44	0.97	0.494
2005	19.000	0.428	0.137	1.94	0.362	0.184
2006	54.033	1.51	0.484	3.54	3.91	2.00
2007	7.668	0.125	0.0401	0.476	0.081	0.0413
2008	8.233	0.216	0.0692	0.906	0.583	0.298
2009	8.280	0.156	0.0498	0.683	0.234	0.119
2010	12.781	0.319	0.102	1.31	0.607	0.309
Total	394.909	14.3	4.565	29.5	22.2	11.3
Minimum	7.668	0.125	0.040	0.476	0.0809	0.0413
Maximum	54.033	2.58	0.826	3.94	4.27	2.18
Mean	24.682	0.892	0.285	1.841	1.39	0.71
Variation	7.0	21	–	8.3	53	–

Note, all data are provided to three significant figures (where possible) to allow data post-processing by other researchers and do not represent a claim of relative accuracy or precision.

and hillslope factors also influence annual mean loads. For example, Zone 6 Line B, a small tributary draining to the South Bay near the Alameda/Santa Clara County boarder, has been rapidly urbanizing during the last decades which might be part of the cause of significantly higher earthflow activity and high sediment yield (27,139 metric t/km^2). Tributaries like this exemplify that watershed-specific empirical field observations are critical for proper physical understanding of landscape processes and any resulting management measures. In addition, we observed the typical inverse relationship between area (km^2) and yield (metric t/km^2); larger watersheds typically have a low drainage density, lower mean watershed slope, and greater riparian sediment storage relative to their smaller counterparts, thus producing lower unit yields.

Based on an eight-station discharge index (see Table 1 footnote for explanation), we estimate that total annual runoff entering the Bay from all small tributaries (a combined area of 8145 km^2) varied from 0.476 to 3.94 km^3 between WYs 1995 and 2010, a variation of 8.3-fold and surprisingly only slightly more variable than runoff from the Sacramento–San Joaquin watershed for the same period (Table 5). Runoff from these small tributaries was less variable during WYs 1995–2010 than experienced during a longer 40-year period 1971–2010 (0.10 km^3–5.33 km^3, a 53-fold variation; mean =1.54 km^3). A 40-year period is more typical of the full range of climatic variability of coastal northern California watersheds. Small tributaries supplied a more variable load to the Bay than the Sacramento–San Joaquin watershed (53-fold compared to just 21-fold variation) and a greater mean annual suspended sediment load (1.39 million metric t equivalent to 170 metric t/km^2 based on the whole watershed area or 212 metric t/km^2/yr based on the area downstream from dams which collectively capture about 1600 km^2) for WY 1995–2010 (Table 5). The WY with the greatest runoff (1995; which differs from that for the Sacramento–San Joaquin watershed) transported 19% of the 16-year total load and the wettest two consecutive WYs (1997 and 1998; the same as the Sacramento–San Joaquin watershed) transported 26% of the total load. This helps to emphasize the importance of observations made during very wet years. Given the mean discharge characteristics, the discharge-weighted mean suspended sediment concentration in discharges from the combined area of all 482 tributaries draining to the Bay from the nine fringing counties was 754 mg/L.

Although the small tributaries in the nine counties surrounding the San Francisco Bay comprise only 5% of the watershed area upstream from the Golden Gate, during the study period these small tributaries collectively contributed 7% of the discharge and 61% of the suspended sediment load. During ten years of the 16-year study period, we estimate that small Bay Area tributaries dominated the fluvial load of suspended sediments to the Bay (Fig. 2). This illustrates the collective importance of small, tectonically active, steep coastal watersheds relative to the larger inland counterparts in the delivery of sediment to coastal areas (c.f. Milliman and Syvitski, 1992). It also likely reflects the effect of dams on Sacramento–San Joaquin watershed which effectively block sediment transport from 48% of the watershed area (Minear,

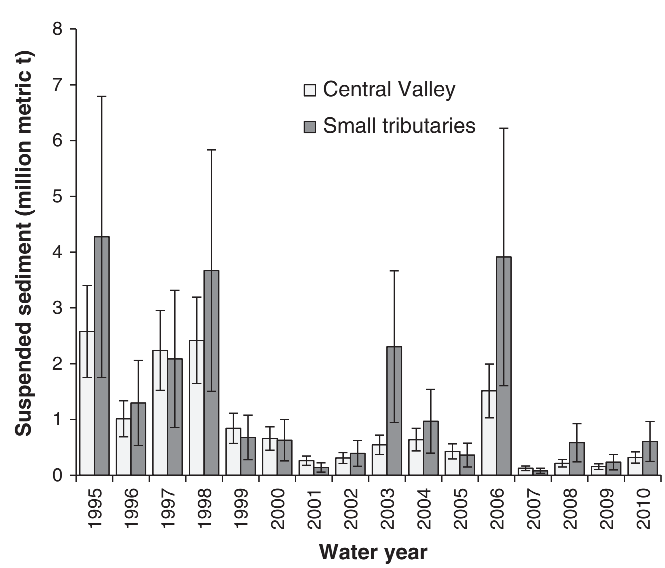

Fig. 2. The temporal comparison between suspended sediment loads entering San Francisco Bay from the Central Valley of California and the 482 small tributaries in the nine-county Bay Area. Although our computations provide support that, for 10 out of 16 yr, small tributaries supplied the majority of external loads, the estimated error bounds around those loads overlap.

2010) and reduce peak flows during floods (Kondolf and Matthews, 1991), in direct contrast to the hydromodification effects of urbanization on the Bay Area small tributaries. As a result, the dominance of small tributaries occurred not only during wetter years but also during drier discharge years. The most extreme examples occurred in WY 2003 (the sixth driest discharge year) when small tributaries supplied a sediment load 4.3-fold higher than that of the Sacramento–San Joaquin watershed and during the second-driest year (WY 2008), when small tributary dominance was 2.8-fold. Overall, 37.1 million metric t of suspended sediment entered the Bay from the combined Golden Gate watershed (162,145 km^2) during the 16-year period, of which we estimate 61% was derived from the small urbanized tectonically active tributaries. Despite overlap in the error bounds (Fig. 2), the preponderance of small tributary dominance and the likelihood that the 16-year mean is more accurate (Toor et al., 2008) lend further credence to these results.

4. Discussion

4.1. Validation of the nine-county small tributary loads

We have developed and demonstrated how environmental data gathered from disparate sources can be obtained and analyzed to provide reliable and useful analyses of suspended sediment load to an important coastal marine ecosystem. All measurements of environmental processes carry error and bias associated with instrumentation, a varying spatial and temporal deployment array, sample processing, and documentation standards. In the Methods section above, we made substantial effort to consider the error bounds around both the raw data that were used as input, as well as our choices of computation methods. There are rare examples of error bounds on load estimates reported in scientific literature (e.g. Inman and Jenkins, 1999; Conaway et al., in press), yet modeling applications, for example, often require some understanding of data accuracy and precision in relation to sensitivity analysis and calibration procedures.

Although we have high confidence in the loads computed based either on field observations and watershed-specific regression or on regional regression models for each province, we have less confidence in the watershed-specific load estimates based on the land use method applied to 30% of the area of the nine-county small tributary watersheds. However, if we had scaled the empirical measurements up by an area ratio, the loads from our 13 watersheds for which we had the most reliable data (56% of the target area), and which was the method used previously to estimate regional sediment delivery in the Bay Area (e.g. Krone, 1979; Porterfield, 1980; McKee et al., 2003), to the central and southern California coast (Inman and Jenkins, 1999), and for delivery of sediment to world oceans (Milliman and Meade, 1983), we would have computed a total small-tributary annual mean suspended sediment load of 1.54 million metric t; only 10% different than our preferred estimate. In addition, the mean suspended sediment yield that we computed for the combined area of small tributaries in the nine-county Bay Area (212 metric t/km^2/yr), though much greater than for the Sacramento–San Joaquin watershed and reported by most previous authors (Krone, 1979; Porterfield, 1980; McKee et al., 2003), is about half the mean reported for multiple California watersheds (Anderson, 1981: 454 metric t/km^2/yr) and the mean reported for coastal California watersheds (Inman and Jenkins, 1999: 360 metric t/km^2/yr). Anderson also reported a discharge-weighted mean suspended sediment concentration computed across all 61 of his study watersheds of 854 mg/L; again close to our reported mean for the nine-county area (754 mg/L).

Our confidence in our regional scale estimate is also increased by the positive relationship between watershed area and watershed load and the inverse relationship of watershed area to yield (t/km^2/yr). Based on a worldwide dataset for large rivers, Milliman and Meade (1983) suggested that for every ten-fold decrease in basin area, sediment yield increases about 7-fold. In later work, it was recognized that there can be relationships specific to regions or physiographic settings (Milliman and Syvitski, 1992). Based on 13 watersheds where we have empirical field observations (including the Sacramento–San Joaquin watershed but excluding Zone 6 Line B), we observed a 2.8-fold increase in yield for every ten-fold decrease in basin area.

4.2. The role of coastal tectonically active small tributaries versus large rivers

Small continental margin tributaries on the California coast are known to have flashy hydrology, erodible geology, and steep river gradients with direct connections to coastal waters and bays (Lehre, 1981; Griggs and Paris, 1982; Lewicki and McKee, 2010; Conaway et al., in press), whereas larger river basins like the Sacramento–San Joaquin watershed typically have lower mean river gradients and can be dominated by more resistant geology such as granitic rocks that have comparatively lower rates of erosion and sediment production (Milliman and Syvitski, 1992). In addition, we observed greater variability in our smaller coastal systems. The variation in load characteristics was likely, in part, influenced by the decoupled runoff-producing processes of the Sacramento–San Joaquin watershed and the coastal watersheds. There are numerous flood control and water supply dams in the Sacramento–San Joaquin watershed that collectively capture about 48% of the watershed upstream from Mallard Island at the head of San Francisco Bay (Minear, 2010). These dams are specifically operated to capture, delay and diminish discharge from spring snow melt and so eliminate or dampen many of the peak discharges that are normally crucial for sediment transport (see Kondolf and Matthews, 1991, Table 12 that shows a 2–69% reduction in 2-year return interval flows below Central Valley dams). For example, since regulation by Shasta Dam in December 1943, maximum discharge in the Sacramento River at the Bend Bridge (USGS station number 11377100) has been 4587 m^3/s. In contrast, between WY 1879 and 1943, 11 peaks of >4500 m^3/s occurred, the largest of which was 8240 m^3/s. Central Valley dams likely skew the sediment transport relationship more towards large events than the historical natural condition. Medium sized events (~2–10-year return interval flows) that might previously have constituted a range of 'dominant discharges' for sediment transport are now absorbed by the many dams, but events like the 1997 floods exceed the flood storage capacity and trigger big releases, forming the new dominant discharges. In contrast to dampening in the Central Valley, the precipitation–discharge characteristics of the coastal small tributary watersheds have been amplified through urbanization and hydromodification. Despite the dampening effects of dams, the largest discharges from the Sacramento–San Joaquin watershed still occur when warm rains fall on accumulated snow typically in the months of January through April, whereas runoff from coastal small tributaries is usually the result of sustained heavy coastal Pacific rainfall falling on saturated soils in December, January, and February.

Here, we accounted for most of those factors primarily by using as much empirical field data as possible in our methodology. Although the large Sacramento–San Joaquin watershed still provides the largest source of sediment for a single river system in the Golden Gate watershed (39% of the annual mean load; Fig. 3), our analysis provides new evidence that the mean yield (t/km^2/yr) of steeper coastal tectonically active small tributaries is 12-fold greater than the larger Sacramento–San Joaquin watershed, more than 100-fold greater in some of the larger of the erosive watersheds of the North Bay province, and more than 1000-fold greater in some of the urbanizing small tributaries. The ten largest small tributary watersheds provide 35% of the total mean annual suspended sediment load; the largest 30 small tributaries provide 43% of the mean annual suspended sediment load (Fig. 3). The step in the upper middle of the graph is caused by Zone 6 Line B, a small (2.1 km^2) watershed with particularly high sediment yield at present that is possibly due to recent urbanization playing a role in increased earthflow activity.

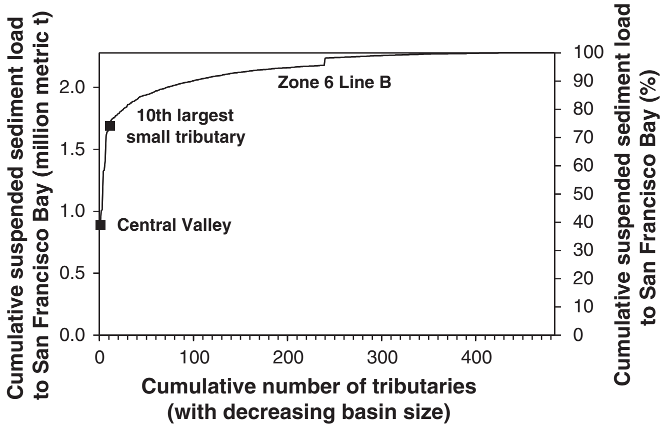

Fig. 3. Cumulative suspended sediment load entering the Bay from the Central Valley and the 482 small tributaries in the nine-county Bay Area.

Our results provide further context for previously published yields for small coastal California watersheds draining to the coastal marine environment (Lehre, 1981: Lone Tree Creek, 180 t/km^2; Anderson, 1981: 61 northern California watersheds, 4–2121 t/km^2; Inman and Jenkins, 1999: 20 central and southern California coastal watersheds, 10–2650 t/km^2). Further, if we consider maximum suspended sediment concentrations that can occur in some of our small tributaries (Wildcat Creek: 13,400 mg/L; Colma Creek: 19,400 mg/L; Zone 6 Line B: 73,500 mg/L), hyperpycnal sediment discharge (Warrick and Milliman, 2003) may even be occurring on the margins of the Bay during some extreme events.

The Sacramento–San Joaquin watershed is known to have highly episodic sediment discharge to the Bay (McKee et al., 2006). McKee et al. reported that, 3.7% of the mean annual sediment load for any one WY enters the Bay on just one day and 19% is transported in the wettest seven-day period. A similar phenomenon occurs for small tributaries in the nine-county Bay Area, however, at a greater magnitude. For example, based on data for WYs 1995–2010, Alameda Creek, Cull Creek, San Lorenzo, Crow Creek, Zone 6 Line B, Guadalupe River, and Coyote Creek transported 38%, 36%, 42%, 39%, 15%, 27%, and 18% of their annual suspended sediment loads in just one day. In the most extreme case, in WY 2003, Alameda Creek transported 76% of its annual sediment load in one day and 83% in the seven-day period during the storm and on the recession limb of the hydrograph. This one-day and seven-day load constituted 35% and 38% respectively of the total measured 11-year suspended sediment load for WYs 2000–2010. These statistics are similar to the Santa Ana River in southern California which discharges a mean of 90% of its annual sediment load in just three days per year (Warrick and Rubin, 2007), and further exemplify the extreme importance of making field observations for accurate determination of sediment loads during rare high discharge events. These episodic characteristics that are strongly represented in our input data sets provide further support that our regional computations of long-term mean loads are reliable. In addition, the computation structure set up to support the current analysis can be easily augmented in future — perhaps five years hence as more data become available, after a particularly wet year, as bed load data are compiled or as new techniques for estimating sediment loads from the urban areas around the Bay are developed.

4.3. Lack of bed load information

Whereas we show that the estimates of suspended loads are quite accurate at the regional scale, a weakness in the present analysis is the lack of treatment of coarse material transported along the bed. Yet, the fate of fine versus coarse sediment once it enters the Bay is likely quite different. Suspended sediment load is easily reworked and dispersed by tides and wind waves (Schoellhamer, 2002; Downing-Kunz and Schoellhamer, 2013–this issue). In contrast, a greater proportion of coarse sediment will likely remain near a tributary mouth forming a deltaic deposit or nourishing near-field beaches, marshes, or mudflats. Estimates of bed load in relation to suspended load have been proposed for California coastal watersheds of 3.4–19% (Lehre, 1981; Griggs and Paris, 1982; Inman and Jenkins, 1999; Willis and Griggs, 2003). Milliman and Meade (1983) used a ratio of 7–14% for an estimate of bed load transported by rivers to the world oceans. Estimates for supply to San Francisco Bay are on the lower end of these ranges (1.4–6.4%, Krone, 1979; Porterfield, 1980). This may be reasonable given that the slope of most of the small tributaries decreases sharply as they pass from the upland catchments to the Bay plain. The effect of this transition on suspended-sediment transport has recently been studied for one tributary (Downing-Kunz and Schoellhamer, 2013–this issue) and deposition of bed load is likely to be greater. Although many small tributaries enter the Bay via storm drains with no capacity for storage, many larger tributary watersheds in the nine-county Bay Area have managed flood control channels that pass water and sediment from upland catchment areas across the Bay plain. Sedimentation and loss of flood capacity in these flood control channels is a problem (Griggs and Paris, 1982) and sediment can be removed during channel maintenance. As the Bay Area continues to urbanize, bank erosion and bed incision may provide ever greater coarse sediment load (Trimble, 1997). We presently know of about 40 yr of bed load data collected across about ten watersheds in the Bay Area, a diminutive data set compared to the 235 station years of suspended sediment load information collected across 38 watersheds presented and analyzed in the current work. Improved estimates of coarse sediment bed load transport to the Bay will require a regional synthesis of the existing bed load data and a synthesis of sediment storage and removal in the flood conveyance facilities managed by the Bay Area Flood Protection Agencies Association (BAFPAA); a subject of ongoing research by McKee and others.

4.4. Sediment trends and climate variability

San Francisco Bay is often described as the most impacted urban estuary on the West Coast. Between 1849 and 1970, over 40 million kg of mercury was extracted from more than a dozen mining areas within the nine-county Bay Area, most of which was extracted during the gold rush from the New Almaden Mines in the Guadalupe River watershed (South San Francisco Bay) and transported to the Sierra Nevada Mountain Range (eastern California) for gold processing (Conaway et al., 2008). Common mining waste disposal practice involved dumping tailings into the adjacent creek and allowing storm discharges to wash sediment away from the mining site. Subsequently, urban centers expanded, forest timber trees were extracted, and agricultural land was opened up helping to create the need for river management for water supply and flood control. Today more than 13 million people reside in the Golden Gate watershed (which includes 37% of the area of California) and over seven million live in the conurbation of the nine-county Bay Area. These major waves of land use change have led to large, but time-dependent, changes in the load of sediment to San Francisco Bay that has been linked to evidence of sedimentation changes in the Bay (Foxgrover et al., 2004; Jaffe and Foxgrover, 2006; Schoellhamer, 2011; Jaffe et al., 2013).

There is mounting evidence for a trend of initially increasing and then decreasing sediment load entering the Bay from the Sacramento–San Joaquin watershed (Wright and Schoellhamer, 2004; Ganju et al., 2008; Schoellhamer, 2011; Schoellhamer et al., 2013–this issue) spanning 160 yr. The most recent change appears to have occurred in WY 1999 when suspended sediment concentrations appear to have taken a step down (Schoellhamer, 2011). A cumulative double-mass plot (Walling, 2006) illustrates this shift (Fig. 4). The question remains: will this trend hold true if a number of wet years in a row were to occur in a similar manner to the WY 1995–1998 period? California's climate is known to oscillate between predominantly dry periods and predominantly wet periods lasting three to seven years superimposed upon longer

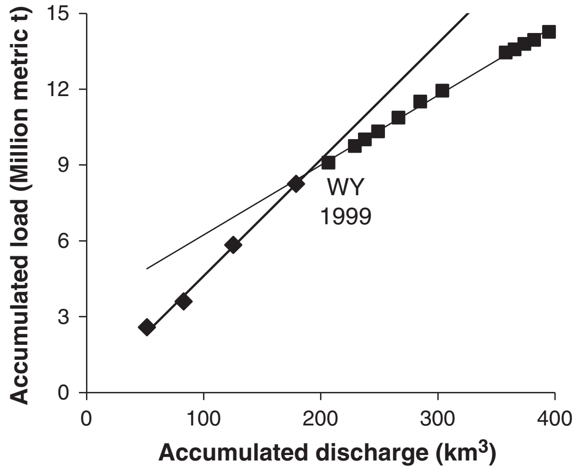

Fig. 4. A cumulative double-mass plot of supply of suspended sediment load from the Central Valley to San Francisco Bay illustrating the change that occurred around water year 1999. Note that water year 2006 was a wet year but load was consistent with the post-1999 relation. Unfortunately, long-term datasets in several of the small tributaries in the nine-county Bay Area have data gaps that negate this kind of analysis.

multi-decadal trends (Inman and Jenkins, 1999). These multi-year climatic fluctuations have been shown to influence mean sediment yield by a factor of 4-fold between wet and dry periods (Inman and Jenkins, 1999). We also observed this phenomenon in both our Sacramento–San Joaquin watershed loads (2.3-fold difference between wet to dry periods before and after 1999) and our small tributaries suspended sediment loads (1.8-fold difference) (Fig. 5). Since there was no significant change in flow during the period (Hestir et al., 2013–this issue), the step change in Sacramento–San Joaquin watershed loads was probably mostly attributable to the step change in suspended sediment concentrations observed at Mallard Island (Schoellhamer, 2011). In contrast, since smaller tributaries are more sensitive to climatic conditions exhibiting much greater flow variability, it is possible that the decreased small tributary loads in post-1999 were due mainly to climate. In general, caution should be exercised when using the currently available data to either hindcast or forecast until another series of wet years have been observed.

Unfortunately, suspended sediment data sets in Bay Area tributaries only extend back to WY 1957, well after the initial mining sediment pulse and subsequent agricultural sediment pulse and into the middle of the post-World War II rapid urbanization period (Schoellhamer, 2011). From 1960 to 2010, human population in the nine-county Bay Area has increased from 3.639 to 7.151 million (Census, 2010) with

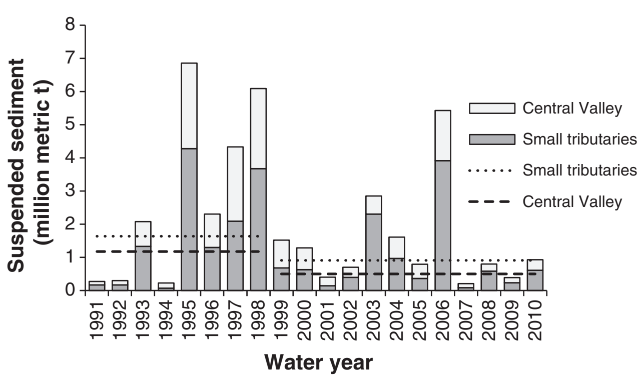

Fig. 5. Step-change in average multi-year suspended sediment loads entering the Bay from both the Sacramento–San Joaquin Rivers draining from the Central Valley and the small tributaries in the nine-county Bay Area before and after water year 1999. Note: data for water year 1991–1994 were not measured but were estimated for both the Sacramento–San Joaquin Rivers and the small tributaries using least squares regression based on annual discharge and annual suspended sediment load.

concomitant land use changes. Unlike the Sacramento–San Joaquin watershed system, it is not possible to apply hindcast estimation methods (Ganju et al., 2008) to determine longer term (pre-1950s) sediment load trends for many hundreds of small tributaries due to lack of data. A problem with using existing records to compute suspended sediment load is that they represent not only response to changing climatic factors but also land use and water-management changes. Therefore they should be viewed as a snapshot of an evolving land–waterscape (Walling, 2006). Anthropogenic impacts can be erosion or sediment transport enhancing (e.g. land development for agriculture and urban uses; channel bank hardening) or storage enhancing (dams, sedimentation basins). Unfortunately there was a hiatus in basic suspended sediments monitoring in most small tributaries during the 1980s and 1990s (Table 2) that hinders analyses of supply and trends. Therefore there are no continuous data sets to explore trends using a cumulative double-mass plot method. Instead, the linear model procedure in R version 2.15.0 (R Development Core Team, 2012) was employed. Models were evaluated examining whether sampling period affected the slope or y-intercept of a suspended sediment load (SSL) versus instantaneous peak discharge relationship. p values of <0.05 were deemed significant and p values of <0.10 were deemed a trend. Data were log transformed to achieve variance homoscedasticity and normality of residuals. For Alameda Creek, there was a trend of lower log SSL at a given log (instantaneous peak discharge) for later period samples ($p = 0.08$) (Fig. 6). For San Lorenzo Creek, log SSL was lower at a given log (instantaneous peak discharge) for later period samples ($p = 0.023$). For Colma Creek, log SSL was lower at a given log (instantaneous peak discharge) for later period samples ($p = 0.0002$). For Cull Creek, the SSL vs. discharge relationship exhibited a less steep slope for later period samples than earlier period samples (p for slope effect $= 0.025$). Thus, evidence of trends remains incomplete. Only the loads on Colma Creek at South San Francisco showed a strong split in the data between the earlier period when development and urbanization were causing severe erosion in the watershed (Knott, 1973) and a slightly later period when apparently erosional processes had subsided somewhat (Fig. 6).

A similar occurrence probably occurred on the Guadalupe River during the 1950s in response to rapid urbanization and development after World War II and through to the 1970s. Suspended sediment discharge in Guadalupe River has decreased by a factor of 4–8-fold between observations made from 1957 to 1962 and more recent observations between 2003 and 2008 (Schoellhamer, 2011). Porterfield (1980) reported a mean yield for Guadalupe River for WYs 1957–1966 of 295 US tons per square mile (equivalent to 103 metric t/km^2), about 6-fold greater than the mean yield we computed for WYs 1995–2010. We may see a similar trend in the future in the Zone 6 Line B watershed since the sediment production is likely to decrease after the recent urbanization trend ceases or supply from earthflows decreases. It is surprising that only a very weak trend is observed in the Alameda Creek data given recent and rapid urbanization of the tri-city area (population in the combined cities of Dublin, Pleasanton, and Livermore has doubled from 99,000 in 1980 to 197,000 in 2010 (US Census Bureau)). Two dams in the Alameda Creek watershed were completed in 1965 (San Antonio) and 1968 (Del Valle) trapping a combined area of 29% of the watershed. Perhaps sediment loads were already elevated during the earlier period of data collection (1957–1973) such that sediment associated with urban development in recent years has led to similar sediment yields at the watershed scale. These kinds of processes have been observed in relation to dam building and later land use development in other parts of the world (Walling, 2006). So, although conceptually it is reasonably argued that Bay Area small tributaries have gone through periods of increased sediment load to San Francisco Bay during urbanization or development phases (Schoellhamer, 2011), it appears that the suspended sediment load estimates presented here for WYs 1995–2010 represent a period of quasi-stable sediment transport in the context of 3–7 yr oscillations between predominately wet and dry periods.

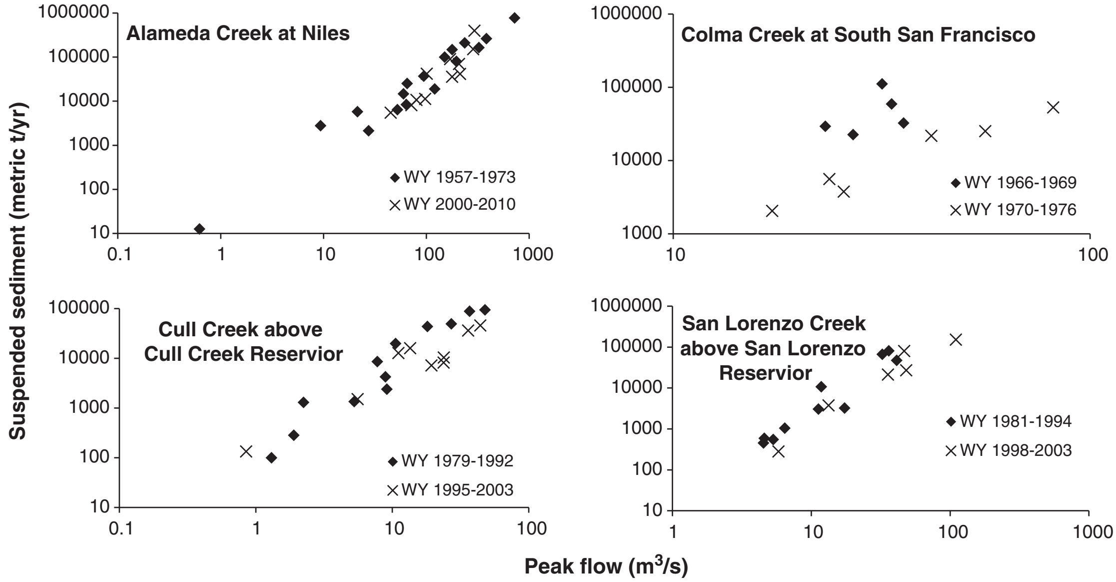

Fig. 6. Long-term suspended sediment data sets in small tributaries draining the San Francisco Bay. With the exception of Colma Creek at South San Francisco, which was undergoing rapid land use conversion and urbanization during the data collection period, the long-term data sets exhibit trends with low probability of being real (see text for details).

To avoid trends associated with land use change and non-stationarity, the early period data for Guadalupe River and Colma Creek were not used in our analysis either in the watershed specific regressions or in the Peninsula/South Bay provincial regression. In addition, the data from Zone 6 Line B was kept separated from the East Bay province regional regression. The addition of further 3–4 WYs of data beyond those used by Lewicki and McKee (2010) also provided enhanced weighting of the dataset towards recent years and subsequent improved confidence that our computations are representative of contemporary loads. A majority of urbanization is still occurring in the outlying regions of the nine counties that fringe the Bay and some of the larger watersheds and is accounted for in the recent monitoring data from our larger creeks and rivers (e.g. Alameda, Coyote). Therefore we have been able to avoid most issues relating to non-stationarity at the decadal scale of our computations. This was a weakness of the previous analysis where stationary discharge or suspended sediment data was assumed for the period WY 1957–2007 (Lewicki and McKee, 2010). Unfortunately, available empirical data are not sufficient to support historical load computations; other methods such as lake or wetland cores, or provenance studies in the Bay hold the most promise.

4.5. Implications for management

Information on suspended sediment loads is important for managing San Francisco Bay ecosystems due to associated degradation of water and sediment quality, recreational amenities, native species habitat, disruption of commercial shipping operations, flood protection, and the availability of sediment for restoring wetlands and mitigating the effects of sea level rise. The annual mean sediment load to San Francisco Bay from all fluvial sources was previously reported to be greater than the mean we report here (2.32 million metric t). Krone (1996) estimated an annual sediment load to the Bay under 1960 conditions of 4.38 million US tons (3.97 million metric t), and predicted 2.56 million metric t under 1990 conditions, and 2.04 million metric t by the year 2020. Based on 1960 conditions, Krone (1996) estimated that 24% of the load was supplied by the nine-county small tributaries and, assuming the trend would continue, he predicted that the portion would increase to 37% under 1990 conditions and 46% in 2020 conditions. More recently, Schoellhamer et al. (2005) summarized information for the 1995–2002 period and indicated indicated an average annual sediment load from the Sacramento–San Joaquin watershed and small tributaries combined of about 2.8 million metric t. The downward trend of sediment load to the Bay has positive implications for maintenance of waterways. The San Francisco Bay and Delta is harbor to five shipping ports and five oil refineries. About 1.61 million cubic yards (1.23 million m^3) (2011 reported volume) of sediment is dredged annually from shipping channels in San Francisco Bay to maintain or increase capacity and functionality and disposed of outside of the Bay (LTMS, 2012). This sediment is presently deposited off shore at deep-ocean disposal sites as considerable cost, or placed in wetlands during restoration (Callaway et al., 2011). The downward trend in sediment load from the Sacramento–San Joaquin watershed to the Bay may help to relieve the need for dredging ship channels and harbors in the Bay and Delta. However, there are possible ramifications for sediment erosion of coastal beaches (Barnard et al., 2013–this issue). The new temporally and spatially defined loads from small tributaries, if compared to the annual removal volumes, may help to better understand the sources of sediment currently being removed by dredging and the implications.

Unfortunately, the ramifications of this new sediment load information are perhaps negative for pollutants, phytoplankton trends, wetland restoration, and mitigation of sea level rise through the process of coastal accretion. Sediments can be pollutants themselves, attenuating light and controlling primary production (Cloern et al., 2005). Sediments carry particle-associated pollutants, such as carbon, phosphorus, mercury, PCBs, PAHs, and legacy organochlorine pesticides (Oram et al., 2008; David et al., 2009; Conaway et al., in press). Given the downward trend in suspended sediment load from the Sacramento–San Joaquin watershed (Wright and Schoellhamer, 2004; Ganju et al., 2008; Schoellhamer, 2011) and the relatively clean nature of the Sacramento–San Joaquin watershed-derived sediment particles on a mass per unit mass basis (David et al., 2009) compared to suspended sediments emanating from urban areas around the Bay (Oram et al., 2008), and the uncertain evidence of a trend in sediment loads from smaller tributaries, it seems likely that the ratio of dirty-to-clean sediment will continue to rise. In addition, if the Bay remains net erosional (Foxgrover et al., 2004; Jaffe and Foxgrover, 2006; Jaffe et al., 2013), there may be continued release of legacy pollutants such as mercury and PCBs (Davis et al., 2007; Davis et al., 2012). Maintaining or improving water and sediment quality in San Francisco Bay may require increasing efforts by urban managers around the Bay. One useful outcome for improved sediment load information in relation to pollutant management is the use of sediment loads (metric t) in combination with pollutant concentrations on particles (mg/kg or g/metric t) to derive first-order estimates of pollutant loads, a particularly useful tool for emerging pollutants where more detailed information is usually sparse. However, any change in the estimates of regional-scale suspended sediment loads implies a change in the estimates of regional-scale pollutant loads. Here, our regional-scale prediction is greater than previous predictions (e.g. Krone, 1979) by at least 30%.

Recently, evidence is growing that the Bay's ability to assimilate nutrients may be declining. The increase in the prevalence of harmful algal blooms (Cloern et al., 2005) and the magnitude of both baseline chlorophyll concentrations and spring bloom concentrations, in addition to the recent appearance of autumn blooms may be in part a result of reduced sediment load, lower water column turbidity and enhanced light penetration (Cloern et al., 2007, 2010). In relation to wetland restoration on the Bay margin, both the downward trends of sediment load, in addition to the possible downward trend in the sediment quality, suggest a more bleak future. This improved understanding of suspended sediment load may be critical for predicting resource availability and the accretion rate in restored tidal habitats (Williams and Orr, 2002), although sedimentation processes are likely, in many restoration projects, to be mediated by vegetation and proximity to the channel (Culberson et al., 2004). If sediment supply does not support the generation of substrate for vegetation, some restoration projects may fail to keep up with sea level rise and reduce protection of adjacent upland structures such as flood-protection levees. The watershed-specific mean annual sediment yields provided here (Table 3) and annual variations (not presented but available upon request from the authors) should provide key information for managers and engineers in relation to wetland restoration design.

Since suspended sediment supplied by small tributaries enters the Bay from literally hundreds of small watersheds, it is most likely deposited downstream from the head of tide in the lower tidal portions of flood control channels or on the Bay margins (Downing-Kunz and Schoellhamer,2013–this issue). From there it can then be slowly reworked by tides, wind and currents into the axis of the Bay. Once on the axis, it may be transported longer distances before being deposited elsewhere in the Bay or offshore in the Pacific Ocean (Krone, 1979). The relatively small freshwater discharge from small tributaries is unlikely to flush it out of the Bay. Thus, if we distribute the computed annual mean small tributary suspended sediment load (1.39 million metric t) along the 750 km open water Bay shoreline, an estimated ~18,500 metric t/km of shoreline may continue to be supplied to the area near the fluvial–tidal interface and be available for restoration per decade; although planning to receive this mass of the sediment will be hampered by the tendency for a series of wet and dry years to cluster for a period of three to seven years in a row (Inman and Jenkins, 1999) (Fig. 5). In contrast, sediment supplied from the Sacramento–San Joaquin watershed enters the Bay at only one location and the mean discharge from the Sacramento–San Joaquin watershed is much greater, at approximately 25 km^3 annually (McKee et al., 2006). The load from the Sacramento–San Joaquin watershed is only slightly less unpredictable at the decadal scale (Fig. 5) and the discharge magnitude of Sacramento–San Joaquin watershed can flush some of the flood load suspended sediment offshore in a single event (Ruhl et al., 2001). For example, an estimated 231,000 metric t of sediment formed a plume adjacent to and outside the Golden Gate Bridge during a February storm in 1998 (Mertes and Warrick, 2001). The implication is that sediment load from small tributaries may now, and perhaps has had, for the last many decades, a larger impact on siltation in near-shore marinas, shipping facilities, and wetlands than sediment derived from the Sacramento–San Joaquin watershed.

5. Conclusions

New robust, temporally and spatially explicit, suspended sediment loads have been computed for San Francisco Bay using a thorough compilation of a large but formally disparate data set. We combined a series of empirically based methods with a focus on maintaining information on much of the episodic climatic influences as well as human perturbations to address issues of non-stationarity typical of the California coastal watershed ecosystem. The loads computed are less than those previously reported for the Sacramento–San Joaquin watershed and greater than those previously reported for the small tributaries in the nine-county Bay Area. These two factors support a paradigm shift in the way we understand the allochthonous sediment load and sediment budget for San Francisco Bay. This new understanding has direct implications for the load and fate of pollutants, maintenance dredging for shipping and recreational marinas, nutrient-related water quality, flood protection, sediment load for wetlands restoration in areas fringing the Bay, and protection of near-shore infrastructure against sea level rise. Weaknesses in the current analysis include the paucity of suspended sediment data for dominantly urban land use areas, the absence of bed load information, and assumptions about the trapping efficiency of flood control infrastructure that conveys upland and urban runoff through the fringing urban areas on the Bay plain. These weaknesses are the subject of ongoing research by McKee and others and should be addressed to support improved Bay management.

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References

ABAG, 2000. Existing Land Use in 2000: Data for Bay Area Counties. Bay Area Association of Governments, Oakland, California, USA (DVD. http://www.abag.ca.gov/).

Anderson, H.W., 1981. Sources of sediment-induced reductions in water quality appraised from catchment attributes and land use. Journal of Hydrology 51, 347–358.

Barnard, P.L., Foxgrover, A.C., Elias, E.P.L., Erikson, L.H., Hein, J.R., McGann, M., Mizell, K., Rosenbauer, R.J., Swarzenski, P.W., Takesue, R.K., Wong, F.L., Woodrow, D.L., 2013. Integration of bed characteristics, geochemical tracers, current measurements, and numerical modeling for assessing the provenance of beach sand in the San Francisco Bay Coastal System. Marine Geology, Special Issue SF Bay 345, 181–206 (this issue).

Bokuniewicz, H.J., Gebert, J., Gordon, R.B., 1976. Sediment mass balance of a large estuary, Long Island Sound. Estuarine and Coastal Marine Science 4, 523–526.

Brown III, W.M., Jackson Jr., L.E., 1973. Erosional and depositional provinces and sediment transport in the south and central part of the San Francisco Bay region, California. Miscellaneous Field Studies Map 515. Interpretative Report 3.

Brown III, W.M., Jackson Jr., L.E., 1974. Sediment source and deposition sites and erosional and depositional provinces, Marin and Sonoma Counties, California. Miscellaneous Field Studies Map 625. Interpretative Report 7.

Buchanan, P.A., Morgan, T.L., 2011. Summary of suspended sediment concentration data, San Francisco Bay, California, water year 2008. US Geological Survey, Data Series Report, 634.

Callaway, J.C., Parker, V.T., Vasey, M.C., Schile, L.M., Herbert, E.R., 2011. Tidal wetland restoration in San Francisco Bay: history and current issues. San Francisco Estuary and Watershed Science 9 (3).

Census, 2010. Human Population Census Data for San Francisco Bay Area (Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco).

Association of Bay Area Governments (http://census.abag.ca.gov/bayarea.htm (Cited March, 2012)).
CGS, 2006. Simplified geological map of California, map sheet 57. California Geological Survey.California Department of Conservation, Sacramento, California (http://www.conservation.ca.gov/cgs/information/publications/ms/Documents/MS057.pdf).
Chin, A., 2006. Urban transformation of river landscapes in global context. Geomorphology 79, 460–487.
Cloern, J.E., Schraga, T.S., Lopez, C.B., Knowles, N., Labiosa, R.G., Dugdale, R., 2005. Climate anomalies generate and exceptional dinoflagellate bloom in San Francisco Bay. Geophysical Research Letters 32, L14608.
Cloern, J.E., Jassby, A.D., Thompson, J.K., Hieb, K.A., 2007. A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay. Proceedings of the National Academy of Sciences 104 (47), 18561–18565.
Cloern, J.E., Hieb, K.A., Jacobson, T., Sansó, B., Di Lorenzo, E., Stacey, M.T., Largier, J.L., Meiring, W., Peterson, W.T., Powell, T.M., Winder, M., Jassby, A.D., 2010. Biological communities in San Francisco Bay track large-scale climate forcing over the North Pacific. Geophysical Research Letters 37, L21602 (6 pp.).
Conaway, C.H., Black, F.J., Grieb, T.M., Roy, S., Flegal, A.R., 2008. Mercury in the San Francisco estuary. Reviews of Environmental Contamination and Toxicology 194, 29–54.
Conaway, C.H., Draut, A.E., Echols, K.R., Storlazzi, C.D., Ritchie, A., (2013). Episodic suspended sediment transport and elevated polycyclic aromatic hydrocarbon concentrations in a small, mountainous river in coastal California. River Research Applications (in press).
Culberson, S.D., Foin, T.C., Collins, J.N., 2004. The role of sedimentation in estuarine marsh development within the San Francisco Estuary, CA, USA. Journal of Coastal Research 20, 228–240.
David, N., McKee, L.J., Black, F.J., Flegal, A.R., Conaway, C.H., Schoellhamer, D.H., Ganju, N.K., 2009. Mercury concentrations and loads in a large river system tributary to San Francisco Bay, California, USA. Environmental Technology and Chemistry 28 (10), 2091–2100.
Davis, J.A., Hetzel, F., Oram, J.J., McKee, L.J., 2007. Polychlorinated biphenyls (PCBs) in San Francisco Bay. Environmental Research 105, 67–86.
Davis, J.A., Yee, D., Grenier, L., McKee, L.J., Greenfield, B.A., Looker, R., Austin, C., Marvin-DePasquale, M., Brodberg, R., Blum, J., 2012. Reducing methylmercury accumulation in the food webs of San Francisco Bay and its local watersheds. Environmental Research 119, 3–26.
Deng, B., Zhang, J., Wu, Y., 2006. Recent sediment accumulation and carbon burial in the East China Sea. Global Biogeochemical Cycles 20, 3014–3025.
Donigian, A.S., Love, J.T., 2003. Sediment calibration procedures and guidelines for watershed modeling. WEF TMDL 2003, November 16–19, 2003. Chicago, Illinois: WEF Specialty Conference Proceeding.
Downing-Kunz, M.A., Schoellhamer, D.H., 2013. Seasonal variations in suspended-sediment dynamics in the tidal reach of an estuarine tributary. Marine Geology, Special Issue SF Bay 345, 314–326 (this issue).
Dyer, K.R., 1974. The salt balance in stratified estuaries. Estuarine and Coastal Marine Science 2, 273–281.
EPA, 2008. HSPF User Manual. www.epa.gov/waterscience/basins/bsnsdocs.html.
Eyre, Bradley D., McKee, L.J., 2002. Carbon, nitrogen, and phosphorus budgets for a shallow subtropical coastal embayment (Moreton Bay, Australia). Limnology and Oceanography 47, 1043–1055.
Eyre, B., Hossain, S., McKee, L., 1998. A sediment budget for the modified sub-tropical Brisbane River estuary, Australia. Estuarine, Coastal and Shelf Sciences 47, 513–522.
Foxgrover, A.C., Higgins, S.A., Ingraca, M.K., Jaffe, B.E., 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. (25 pp. [URL: http://pubs.usgs.gov/of/2004/1192]).
Ganju, N.K., Knowles, N., Schoellhamer, D.H., 2008. Temporal downscaling of decadal sediment load estimates to a daily interval for use in hindcast simulations. Journal of Hydrology 349, 512–523.
Gilbert, G.K., 1917. Hydraulic-mining debris in the Sierra Nevada. United States Geological Survey Professional Paper 105, 154.
Griggs, G.B., Paris, L., 1982. Flood control failure: San Lorenzo River, California. Environmental Management 6, 407–419.
Hestir, E.L., Schoellhamer, D.H., Morgan-King, T., Ustin, S.L., 2013. A step decrease in sediment concentration in a highly modified tidal river delta following the 1983 El Niño floods. Marine Geology, Special Issue SF Bay 345, 304–313 (this issue).
Hobbs, C.H., Halka, J., Kerhin, R.T., Carron, M.J., 1992. Chesapeake Bay sediment budget. Journal of Coastal Research 8, 292–300.
IEP, 2012a. Dayflow: an estimate of daily average delta outflow. Documentation of the computational scheme. http://www.water.ca.gov/dayflow/documentation/ (Interagency Ecological Program website, cited March 2012).
IEP, 2012b. Dayflow: an estimate of daily average delta outflow. Dataflow data, WY 1956–2010.Interagency Ecological Program (http://www.water.ca.gov/dayflow/output/Output.cfm (Interagency Ecological Program website, cited March 2012)).
Inman, D.L., Jenkins, S.A., 1999. Climate change and the episodicity of sediment flux of small California rivers. Journal of Geology 107, 251–270.
Jaffe, B.E., Foxgrover, A.C., 2006. Sediment deposition and erosion in South San Francisco Bay, California from 1956 to 2005. U.S. Geological Survey Open-File Report 2006–1287. (24 pp. [URL: http://pubs.usgs.gov/of/2006/1287]).
Jaffe, B.E., Foxgrover, A.F., Finlayson, D., 2013. A multi-discipline approach for understanding sediment transport and geomorphic evolution in an estuarine-coastal system: San Francisco Bay. Marine Geology, Special Issue SF Bay.
Knott, J.M., 1973. Effects of urbanization on sedimentation and flood flows in Colma Creek basin, California. US Geological Survey Open file report 3018–04.
Kondolf, G.M., Matthews, W.V.G., 1991. Management of coarse sediment in regulated rivers of California. University of California Water Resources Center, Riverside, Report No.80. (http://escholarship.org/uc/item/5rw9k19j).
Krone, R.B., 1979. Sedimentation in the San Francisco Bay System, in San Francisco Bay: the Urbanized Estuary. In: Conomos, T.J. (Ed.), Pacific Division of the American Association for the Advancement of Science, San Francisco, California, pp. 85–96.
Krone, R.B., 1996. Recent sedimentation in the San Francisco Bay System. In: Hollibaugh, J.T. (Ed.), San Francisco Bay: the Ecosystem. Further Investigations into the Natural History of the San Francisco Bay and Delta With Reference to the Influence of Man. Pacific Division of the American Association for the Advancement of Science c/o California Academy of Sciences, San Francisco, California, pp. 63–67.
Lehre, A.K., 1981. Sediment budget of a small California Coast Range drainage basin near San Francisco. In: Davies, T.R.H., Pearce, A.J. (Eds.), Erosion and Sediment Transport in Pacific Rim Steeplands: I.A.H.S. Publication no. 132, pp. 123–138 (Christchurch, New Zealand).
Leopold, L.B., Maddock Jr., T., 1953. The hydraulic geometry of stream channels and some physiographic implications. United States Geological Survey Professional Paper 252.
Lewicki, M., McKee, L.J., 2010. New methods for estimating annual and long-term suspended sediment loads from small tributaries to San Francisco Bay. IAHS Publication 337, 121–125.
LTMS, 2012. Dredged Material Management Office (DMMO) report of dredging and placement of dredged material in San Francisco Bay in 2011. A Report Prepared by the Dredged Material Management Office (DMMO) for the Long Term Management Strategy Program for San Francisco Bay. (http://www.spn.usace.army.mil/conops/DMMO%202011%20Annual%20Report.pdf).
McKee, L., Leatherbarrow, J., Pearce, S., Davis, J., 2003. A review of urban runoff processes in the Bay Area: existing knowledge, conceptual models, and monitoring recommendations. A Report Prepared for the Sources, Pathways and Loading Workgroup of the Regional Monitoring Program for Trace Substances. SFEI Contribution, 66. San Francisco Estuary Institute, Oakland, Ca.(http://www.sfei.org/sites/default/files/Urban_runoff_literature~000.pdf).
McKee, L.J., Ganju, N.K., Schoellhamer, D.H., 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.
Mertes, L.A.K., Warrick, J.A., 2001. Measuring the output from 110 coastal watersheds in California with field measurements and SeaWiFS. Geology 29, 659–662.
Milliman, J.D., Meade, R.H., 1983. Worldwide delivery of river sediment to the oceans. Journal of Geology 91, 1–21.
Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology 100, 525–544.
Minear, J.T., 2010. The downstream geomorphic effects of dams: a comprehensive and comparative approach. Dissertation submitted to Department of Landscape Architecture and Environmental Planning, University of California, Berkeley. 207 pp. http://udini.proquest.com/view/the-downstream-geomorphic-effects-goid:859254533/.
Moody, J.A., Martin, D.A., 2009. Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. International Journal of Wildland Fire 18, 96–115.
NRCS, 1983. Sediment sources, yields, and delivery ratios. Chapter 6. National Engineering Handbook, Section 3, Sedimentation. US Department of Agriculture, Natural Resources Conservation Service (SCS), Washington DC, USA (6.2–6.19).
Oram, J.J., McKee, L.J., Werme, C.E., Connor, M.S., Oros, D.R., 2008. A mass budget of PBDEs in San Francisco Bay, California, USA. Environment International 34, 1137–1147.
Porterfield, G., 1972. Sediment transport and deposition, Walnut and Pacheco Creeks Contra Costa County, California: August 1965–April 1970. US Geological Survey, Open File Report 3022–01.
Porterfield, G., 1980. Sediment transport of streams tributary to San Francisco, San Pablo, and Suisun Bays, California, 1909–1966. US Geological Survey, Water Resources Investigations Report, 91, pp. 64–80.
R Development Core Team, 2012. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Rantz, S.E., 1971. Suggested criteria for hydrologic design of storm drainage facilities in the San Francisco Bay region. USGS Open File Report 71–341. (69 pp.).
Ruhl, C.A., Schoellhamer, D.H., Stumpf, R.P., Lindsay, C.L., 2001. Combined use of remote sensing and continuous monitoring to analyse the variability of suspended-sediment concentrations in San Francisco Bay, California. Estuarine, Coastal and Shelf Science 53, 801–812.
Schoellhamer, D.H., 2002. Variability of suspended-sediment concentration at tidal to annual time scales in San Francisco Bay, USA. Continental Shelf Research 22, 1857–1866.
Schoellhamer, D.H., 2011. Sudden clearing of estuarine waters upon crossing the threshold from transport to supply regulation of sediment transport as an erodible sediment pool is depleted: San Francisco Bay, 1999. Estuaries and Coasts 34 (5), 885–899.
Schoellhamer, D.H., Lionberger, M.A., Jaffe, B.E., Ganju, N.K., Wright, S.A., Shellenbarger, G.G., 2005. Bay sediment budgets: sediment accounting 101. The Pulse of the Estuary: Monitoring and Managing Contamination in the San Francisco Estuary. San Francisco Estuary Institute Contribution, 411 58–63 (Oakland, CA).
Schoellhamer, D.H., Wright, S.A., Drexler, J.Z., 2012. A conceptual model of sedimentation in the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science 10 (3), 1–25.
Schoellhamer, D.H., Wright, S.A., Drexler, J.Z., (2013). Adjustment of the San Francisco estuary and watershed to decreasing sediment supply in the 20th century. Marine Geology, Special Issue SF Bay 345, 63–71 (this issue).
SFEI, 2012. Watershed boundary layer for urbanized portions of Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco counties that fringe the Bay. Data Generated by a Collaborative and Continually Updated Effort Spanning 20 years by William Lettis and Associates, Oakland Museum of California, and San Francisco Estuary Institute. (http://www.sfei.org/content/gis-data-0).

Shellenbarger, G.G., Wright, S.A., Schoellhamer, D.H., 2013. A sediment budget for the southern reach in San Francisco Bay, CA: Implications for habitat restoration. Marine Geology, Special Issue SF Bay 345, 281–293 (this issue).
Toor, G.S., Harmel, R.D., Haggard, B.E., Schmidt, G., 2008. Evaluation of regression methodology with low-frequency water quality sampling to estimate constituent loads for ephemeral watersheds in Texas. Journal of Environmental Quality 37, 1847–1854.
Trimble, S.W., 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. Science 278, 1442–1444.
Turner, R.E., Rabalais, N.N., Alexander, R.B., McIsaac, G., Howarth, R.W., 2007. Characterization of nutrient, organic carbon, and sediment loads and concentrations from the Mississippi River into the Northern gulf of Mexico. Estuaries and Coasts 30, 773–790.
USGS, 2012a. Water-Quality Data for the Nation. United States Geological Survey (http://nwis.waterdata.usgs.gov/nwis/qw (Cited March 2012)).
USGS, 2012b. The National Elevation Dataset (NED) Seamless Dataset for the Conterminous United States. United States Geological Survey (http://ned.usgs.gov/ (Data were downloaded in 2008)).
Walling, D.E., 1977. Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resources Research 13, 531–538.
Walling, D.E., 2006. Human impact on land–ocean sediment transfer by the world's rivers. Geomorphology 79, 192–216.
Warrick, J.A., Farnsworth, K.L., 2009. Chapter 2.2 — sources of sediment to the coastal waters of the Southern California Bight. In: Lee, H., Normark, B. (Eds.), Earth Science in the Urban Ocean: the Southern California Continental Borderland: Geological Society of America, Special Paper Number 454, pp. 39–52. http://dx.doi.org/10.1130/2009.2454(2.2).
Warrick, J.A., Milliman, J.D., 2003. Hyperpycnal sediment discharge from semiarid Southern California rivers: implications for coastal sediment budgets. Geology 81, 781–784.
Warrick, J.A., Rubin, D.M., 2007. Suspended-sediment rating curve response to urbanization and wildfire, Santa Ana River, California. Journal of Geophysical Research 112, F02018.
Williams, P.B., Orr, M.K., 2002. Physical evolution of restored breached levee salt marshes in the San Francisco Bay Estuary. Restoration Ecology 10 (3), 527–542.
Willis, C.M., Griggs, G.B., 2003. Reductions and fluvial sediment discharge by coastal dams in California and implications for beach sustainability. Journal of Geology 111, 167–182.
Wright, S.A., Schoellhamer, D.H., 2004. Trends in the sediment yield of the Sacramento River, California, 1957–2001. San Francisco Estuary and Watershed Science (on line serial), vol. 2(2) ((May), article 2. http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art2/).
Wright, S.A., Schoellhamer, D.H., 2005. Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento–San Joaquin River Delta. Water Resources Research 41, 1–17.
Yabro, L.A., Carlson, P.R., Fisher, T.R., Chanton, J., Kemp, W.M., 1983. A sediment budget for the Choptank River Estuary in Maryland, U.S.A. Estuarine, Coastal and Shelf Science 17, 555–570.