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A sediment budget for the southern reach in San Francisco Bay, CA: Implications for habitat restoration

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ABSTRACT

The South Bay Salt Pond Restoration Project is overseeing the restoration of about 6000 ha of former commercial salt-evaporation ponds to tidal marsh and managed wetlands in the southern reach of San Francisco Bay (SFB). As a result of regional groundwater overdrafts prior to the 1970s, parts of the project area have subsided below sea-level and will require between 29 and 45 million m^3 of sediment to raise the surface of the subsided areas to elevations appropriate for tidal marsh colonization and development. Therefore, a sufficient sediment supply to the far south SFB subembayment is a critical variable for achieving restoration goals. Although both major tributaries to far south SFB have been seasonally gaged for sediment since 2004, the sediment flux at the Dumbarton Narrows, the bayward boundary of far south SFB, has not been quantified until recently. Using daily suspended-sediment flux data from the gages on Guadalupe River and Coyote Creek, combined with continuous suspended-sediment flux data at Dumbarton Narrows, we computed a sediment budget for far south SFB during Water Years 2009–2011. A Monte Carlo approach was used to quantify the uncertainty of the flux estimates. The sediment flux past Dumbarton Narrows from the north dominates the input to the subembayment. However, environmental conditions in the spring can dramatically influence the direction of springtime flux, which appears to be a dominant influence on the net annual flux. It is estimated that up to several millennia may be required for natural tributary sediments to fill the accommodation space of the subsided former salt ponds, whereas supply from the rest of the bay could fill the space in several centuries. Uncertainty in the measurement of sediment flux is large, in part because small suspended-sediment concentration differences between flood and ebb tides can lead to large differences in total mass exchange. Using Monte Carlo simulations to estimate the random error associated with this uncertainty provides a more statistically rigorous method of quantifying this uncertainty than the more typical “sum of errors” approach. The results of this study reinforce the need for measurement of estuarine sediment fluxes over multiple years (multiple hydrologic conditions) to adequately detail the variability in flux. Additionally, the timing of breaching events for the restoration project could be tied to annual hydrologic conditions to capitalize on increased regional sediment supply.

1. Introduction

There has been increased focus on coastal margin habitat restoration over the last several decades. These habitats serve as a valuable wildlife resource, attenuators of storm waves and flooding, sites for recreation, and opportunities for education. However, there have been large declines in these habitats around the world, generally due to factors such as resource overuse, development, and pollution (Boesch et al., 2001; Jackson et al., 2001). More than 65% of worldwide seagrass and wetland habitats, including tidal marsh, have been lost over roughly the last 300 years (Lotze et al., 2006). Given that more than half of the world's population lives within 100 km of the coast and the rate of population growth is increasing in coastal regions (Martínez et al., 2007), it is safe to assume that coastal habitats will be under increased pressure in the future.

San Francisco Bay (SFB) is a large estuary in Northern California, USA, which is surrounded by a major urban area with a population density of about 8200 people km^{-2} (Lotze et al., 2006). This region has lost nearly 80% of its historic tidal marsh habitat over the last 150 years (Goals Project, 1999), representing a loss of about 60,000 ha. Major restoration activities are underway in the SFB area, where over 10,000 ha of former commercial evaporative salt production ponds have been acquired by federal, state, local, and private interests in an attempt to regain some of the lost wetland habitats that historically surrounded the estuary.

The salt ponds around SFB were created over the last 150 years from tidal marsh by constructing levees to isolate the wetlands from the bay and create ponds (Goals Project, 1999). The South Bay Salt Pond Restoration Project (http://www.southbayrestoration.org/), the largest urban wetland restoration project in the US, plans to reclaim about 6000 ha of former salt ponds in south SFB to create a blend of tidal marsh and managed wetland habitats. A major goal of

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the restoration project is to create habitat that can support endangered species and over-wintering and migrating birds that travel along the Pacific Flyway. However, because of groundwater overdrafts in previous decades, parts of the project area have subsided below mean tide level (MTL) — the elevation at which salt marsh plants typically begin to colonize. It is estimated that between 29 and 45 million m^3 of sediment would be required to raise all of the subsided project areas to MTL (U.S. Fish and Wildlife Service and California Department of Fish and Game, 2007). If tidal marsh habitat is desired for these ponds, sediment will be required for the project. The question arises: is there enough sediment naturally available for the successful tidal marsh restoration of these lands?

The far southern reach of SFB has only a few potential sources of natural sediment. The tributaries to this reach provide sediments during the wet season, while there are only minimal inflows during the dry summer season. Three waste-water treatment plants discharge to this area of SFB. There are no definitive plans to import dredge material into the reach or project area. There will be limited dredging in the project area, primarily to breach or lower existing levees and direct water flow into relic marsh channels in the ponds. The only other main potential allochthonous sediment source in this reach would be tidal transport from the rest of the bay through the Dumbarton Narrows. The objectives of this study are to: 1) compare the sediment fluxes from the two main local tributaries to the tidal sediment flux measured at the bayward margin of the reach (Dumbarton), 2) compute a sediment budget for this reach of SFB, and 3) determine if this reach serves as a source or sink of sediment to greater SFB. In addition, the results of the sediment budget are compared to the subsided accommodation space in the restoration project area to determine the feasibility of using the natural supply of sediment for the project needs.

2. Regional setting

San Francisco Bay is the largest estuary on the Pacific coast of the United States. Freshwater enters the head of the estuary primarily via the Sacramento and San Joaquin River Delta on the east side of the bay area, and salt water enters the mouth of the estuary through the narrow Golden Gate on the west end (Conomos et al., 1985). Numerous local tributaries enter on the margins of SFB, the largest in terms of flow being the Napa River, Alameda Creek, and the Guadalupe River (Webster et al., 2005). SFB has a channel-shoal morphology, with narrow, deep channels surrounded by extensive areas of shallow water and mudflats (Fig. 1, Conomos et al., 1985). Far south SFB is the southernmost reach of SFB. The reach is bounded on the bayward side by the Dumbarton Narrows, across which spans the Dumbarton Bridge (Figs. 1 and 2). The two major tributaries Guadalupe River and Coyote Creek enter at the southern end of the reach. The average water depth in this reach of the bay is 2.6 m and the surface area is 34 km^2, both at mean tide level (Hager and Schemel, 1996), maximum depth is about 20 m, and the mixed, semi-diurnal tide range is roughly 3 m. Three municipal waste-water treatment plants (WWTP) discharge to this reach. This region of California experiences a Mediterranean climate, with cool, wet winters and warm summers with strong diurnal winds. Most rainfall occurs between October and April, and hydrologic 'Water Years' are defined locally as 1 October through 30 September, with the spring/summertime year as the Water Year (WY; e.g., WY2011 runs from 1 October 2010 through 30 September 2011).

3. Material and methods

3.1. Tributaries, precipitation, and wastewater

Sampling locations are depicted in Fig. 1. The two main tributaries are gaged with existing USGS stream and suspended-sediment gaging stations on the Guadalupe River (station 11169025) and Coyote Creek (station 11172175). Both stations are located just upstream of tidal influence. A daily record of stream discharge is available from each location, and a daily flux of suspended sediment is available between October 1 and April 30 of a given Water Year (during the wet season). Details on these two sites can be found on the USGS National Water Information System website (http://waterdata.usgs.gov/nwis). Published data were available for Guadalupe River from 23 May 2002–30 September 2011 (discharge) and 1 November 2002–30 April 2011 (suspended sediment), while Coyote Creek data included 1 October 2003–30 September 2011 (discharge) and 1 October 2003–30 April 2011 (suspended sediment, no data were collected during winter 2008).

Several additional tributaries enter this reach of SFB. Individually, they have substantially smaller discharge than Guadalupe River and Coyote Creek and tend not to be reliably gaged for flow or suspended sediment. In order to estimate the contribution of these watersheds to the water and sediment budget, we estimated the watershed areas for the gaged and ungaged watersheds and scaled the Coyote Creek and Guadalupe data by the ungaged watershed area. The majority of the tributaries are in Santa Clara County along the west and south side of far south SFB. Tributary watershed areas, including Coyote Creek and the Guadalupe River, were obtained from Santa Clara Basin Watershed Management Initiative (2000). The area of the ungaged watersheds on the east side of the reach was estimated using the USGS StreamStats web-based tool (streamstats.usgs.gov). Combined, the Coyote Creek and Guadalupe River watersheds cover about 55% of the total drainage area of far south SFB, while the remaining 45% of the drainage area is ungaged. Therefore, the fraction of the sediment contributed by the ungaged tributaries was estimated as 0.82 of the combined Coyote Creek and Guadalupe River fluxes.

Local precipitation data were obtained from the Union City location (station 171) on the California Irrigation Management Information System website (http://wwwcimis.water.ca.gov/). Data from both sources have been quality assessed and controlled and are considered to be of high quality. The three WWTP that discharge to this reach are for the cities of Palo Alto, Sunnyvale and San Jose/Santa Clara. Estimates of this discharge and the average total suspended solids in the wastewater were obtained from the City of San Jose (2012).

3.2. Dumbarton Bridge

A continuous time series of suspended-sediment flux (SSF) at the Dumbarton Bridge was computed for the study period (12 November 2008–30 September 2011) using a combination of high frequency measurements (15-minute intervals) of index quantities (Ruhl and Simpson, 2005; Levesque and Oberg, 2012) and periodic measurements (monthly to quarterly) of water discharge and cross-sectionally averaged suspended-sediment concentration (SSC). Calibrations of the index quantities to cross-section-averaged quantities were used to develop time series of water discharge, SSC, and SSF through the cross-section. Uncertainty was estimated based on a Monte Carlo simulation approach parameterized using the regression residuals from the instrument calibrations.

3.2.1. Data collection

An acoustic Doppler current profiler (ADCP, Nortek Aquadopp 1000 kHz, NortekUSA, Boston, MA, USA) was used to collect water velocity, pressure, and acoustic backscatter data at 15-minute intervals. The instrument was installed in November 2008 and mounted on a pier of the Dumbarton Bridge (Fig. 2), oriented to profile at an angle of ~18° downward toward the bed (Fig. 3). Velocity profiles were collected in fifty 50 cm bins with a blanking distance of 50 cm. Pressure data were corrected for changes in barometric pressure, as measured on the bridge pier. Velocity data were corrected for changes in salinity using data collected during ~weekly–monthly cruises of San Francisco Bay (http://sfbay.wr.usgs.gov/access/wqdata/). Turbidity was measured with an optical sensor (DTS-12, FTS, Victoria, BC, Canada; 15-minute interval) attached to a cable extended alongside the bridge pier (Fig. 3). Instrument

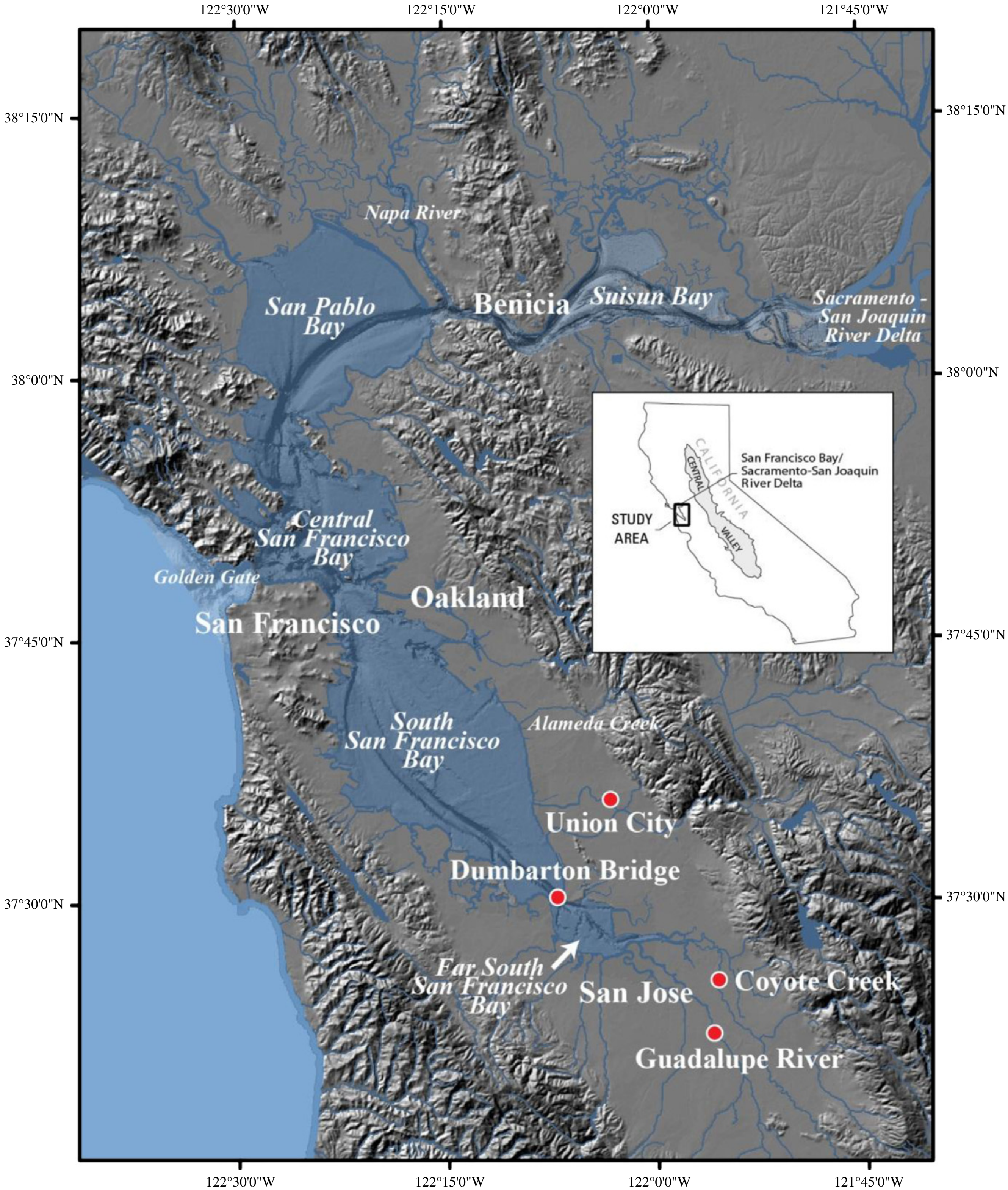

Fig. 1. A map of the study region. The far south San Francisco Bay reach and the location of sediment flux (Dumbarton Bridge, Coyote Creek, and Guadalupe River) and precipitation (Union City) sampling sites are identified.

servicing and data processing conformed to the methods presented in Wagner et al. (2006).

Water discharge and cross-section integrated SSC were measured using standard USGS procedures (Edwards and Glysson, 1999; Mueller and Wagner, 2009). Discharge, mean velocity, and cross-section area were measured with a boat-mounted ADCP (Workhorse Monitor, 1200 kHz, Teledyne RDI, Poway, CA, USA) along moving-boat transects with positioning from differential GPS (AG132, Trimble Navigation Limited, Sunnyvale, CA, USA; Fig. 2). Moving-boat discharge transects were roughly 500 m long. Cross-section SSC was measured with a USGS D-96 suspended-sediment sampler using the Equal-Discharge Increment (EDI) method (Edwards and Glysson,

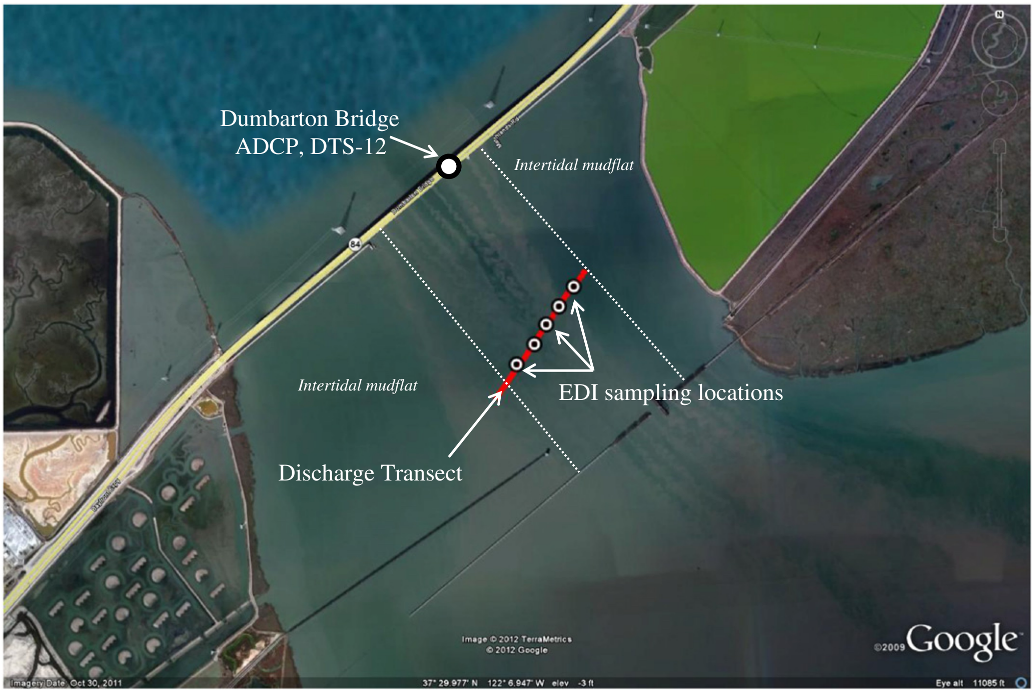

Fig. 2. A detailed image of the Dumbarton Narrows study area showing the location of the index and calibration measurements. White dotted lines represent the approximate location of the channel, with extensive areas of shallow water and intertidal mudflats immediately adjacent. The discharge transect is roughly 500 m wide. A recently constructed managed pond for the South Bay Salt Pond Restoration Project is visible in the lower left corner of the image.

1999; Fig. 2). Measurement of velocity-weighted cross-sectionally averaged SSC accounts for spatial correlation of mean velocity and SSC. This is not true during periods of bidirectional flow, which usually occur only near slack tide when the mean velocity is small and sampling does not occur. Discharge was measured 200 times and cross sectional SSC was measured 55 times during the study.

3.2.2. Instrument calibrations

After editing the time series for biological fouling and instrument drift, calibrations were developed between index quantities (velocity, pressure, and turbidity; bridge-based measurements) and cross-section quantities (mean velocity, cross-section area, and SSC; boat-based measurements). Mean velocity was calibrated to an index velocity measured by the bridge-mounted ADCP (Eq. 1; Fig. 4); the range covering bins from 4.5 to 9 m from the instrument provided the best calibration. Cross-section area was calibrated to pressure (stage) measured by the bridge-mounted ADCP (Eq. 2, Fig. 4). Cross-section SSC was calibrated to turbidity measured by the DTS-12 (Eq. 3, Fig. 4). Fig. 4 shows these calibrations, as well as histograms of the residuals from the calibration equations, which are used in the uncertainty analysis described in the next section.

$$U_{xs} = 0.76U_i - 0.033, R^2 = 0.99, p \ll 0.001 \quad (1)$$

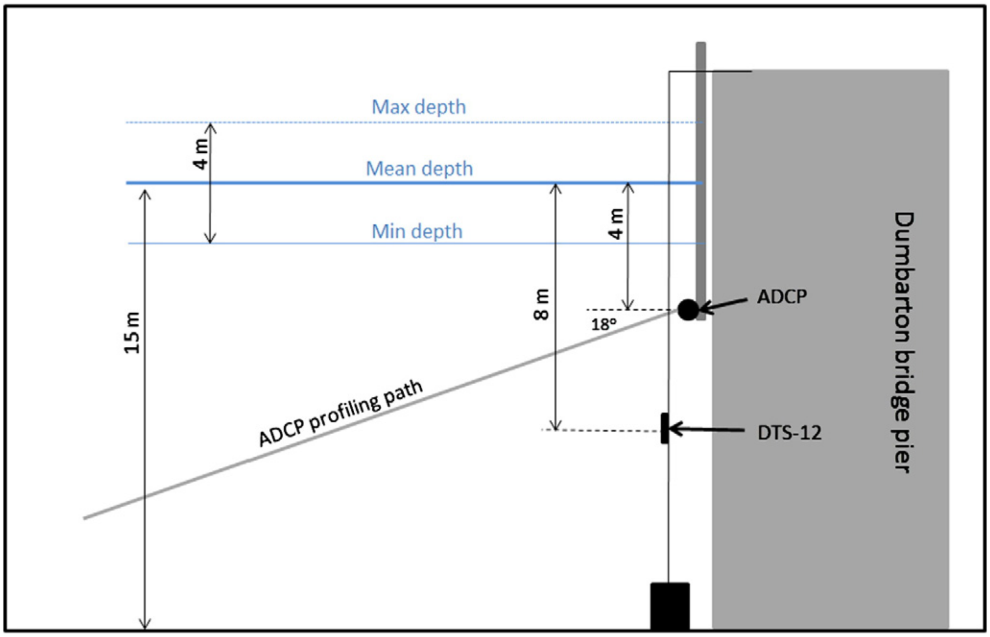

Fig. 3. Schematic of the monitoring instrumentation mounted on the Dumbarton Bridge pier.

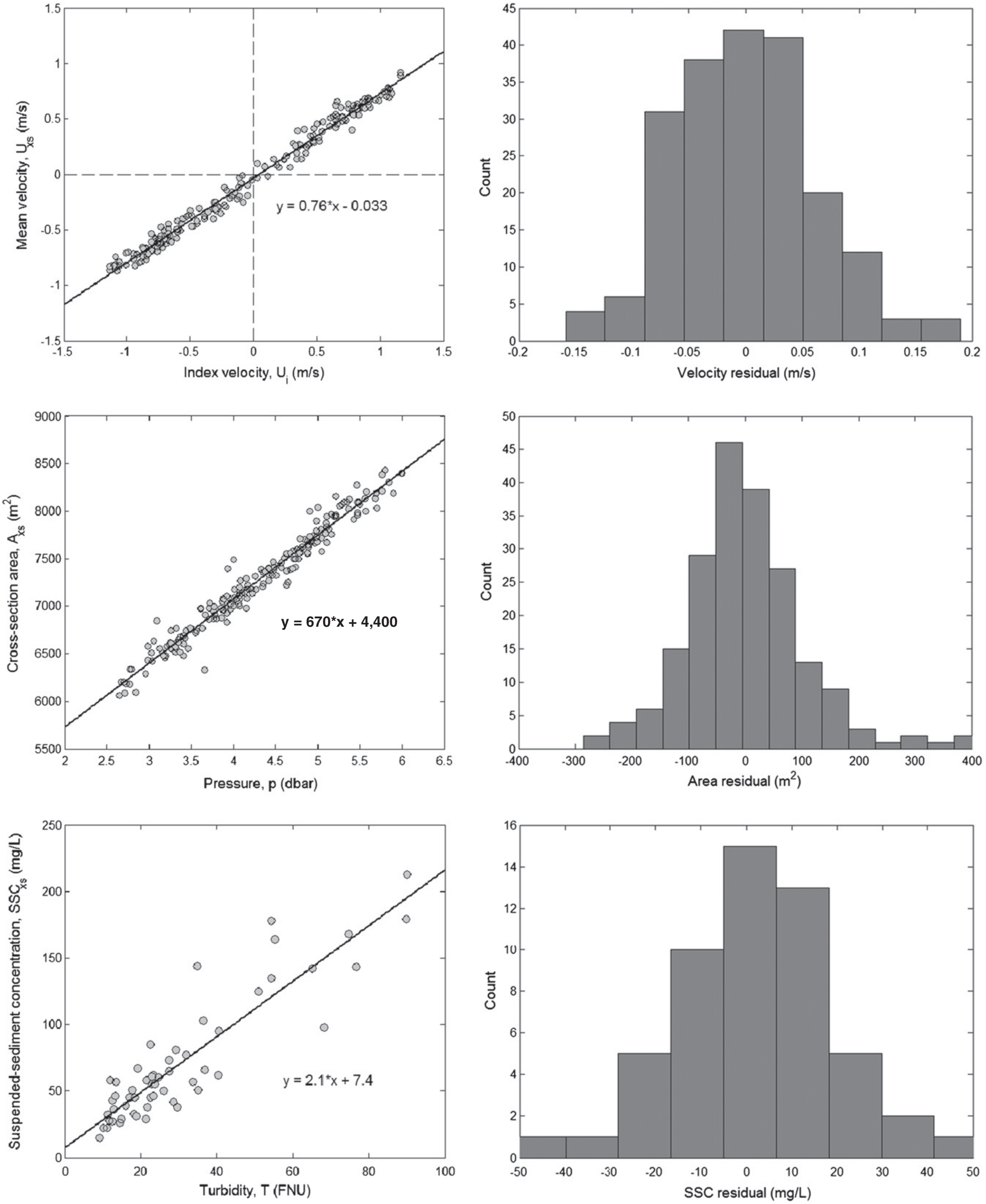

Fig. 4. Instrument calibrations and histograms of the residuals from the linear least-squares fits between the calibration and index variables.

$$A_{xs} = 670p + 4400, R^2 = 0.96, p \ll 0.001 \tag{2}$$

$$SSC_{xs} = 2.1\,T + 7.4, R^2 = 0.81, p \ll 0.001. \tag{3}$$

U_{xs} is the mean velocity in the cross-section, U_i is the index velocity, A_{xs} is cross-section area, p is pressure, SSC_{xs} is the mean suspended-sediment concentration in the cross-section, and T is turbidity. The three calibrations result in continuous time series of U_{xs}, A_{xs}, and SSC_{xs}, which yield time series of water discharge ($Q = U_{xs}A_{xs}$) and suspended-sediment flux ($Q_s = Q\,SSC_{xs}$). Small gaps in velocity data due to biological fouling were filled with data from adjacent days. Approximately 18% of the turbidity data were removed due to fouling. Gaps in turbidity were filled using a calibration between turbidity and acoustic backscatter, yielding a turbidity time series with 97% good data. The remaining 3% was filled with linear interpolation. The turbidity and velocity time-series missing data were filled prior to applying the calibrations. Continuous time-series were necessary for computing sediment budgets.

3.2.3. Flux calculations and uncertainty analysis

Uncertainty in the computed water discharge and SSF arises from errors in field and laboratory measurements, as well as potential biases between index and cross-section quantities. This uncertainty is apparent in the scatter in the calibration plots (Fig. 4). We estimated uncertainty (from random error) using a Monte Carlo simulation approach that incorporates the residuals from the calibrations as random variables. Calibration residuals were modeled as normally distributed (Fig. 4). For each calibration, 100,000 realizations of the calibrations were simulated by 1) randomly sampling the residuals (normal distributions), 2) creating simulated calibration data by adding a random normally distributed residual to the predicted value from Eqs. 1–3 for each data point, and 3) fitting linear regressions to the simulated data. This procedure yields distributions of 100,000 slopes and intercepts for each calibration (Fig. 5). Fig. 5 indicates that the slopes and intercepts are normally distributed (as expected), with

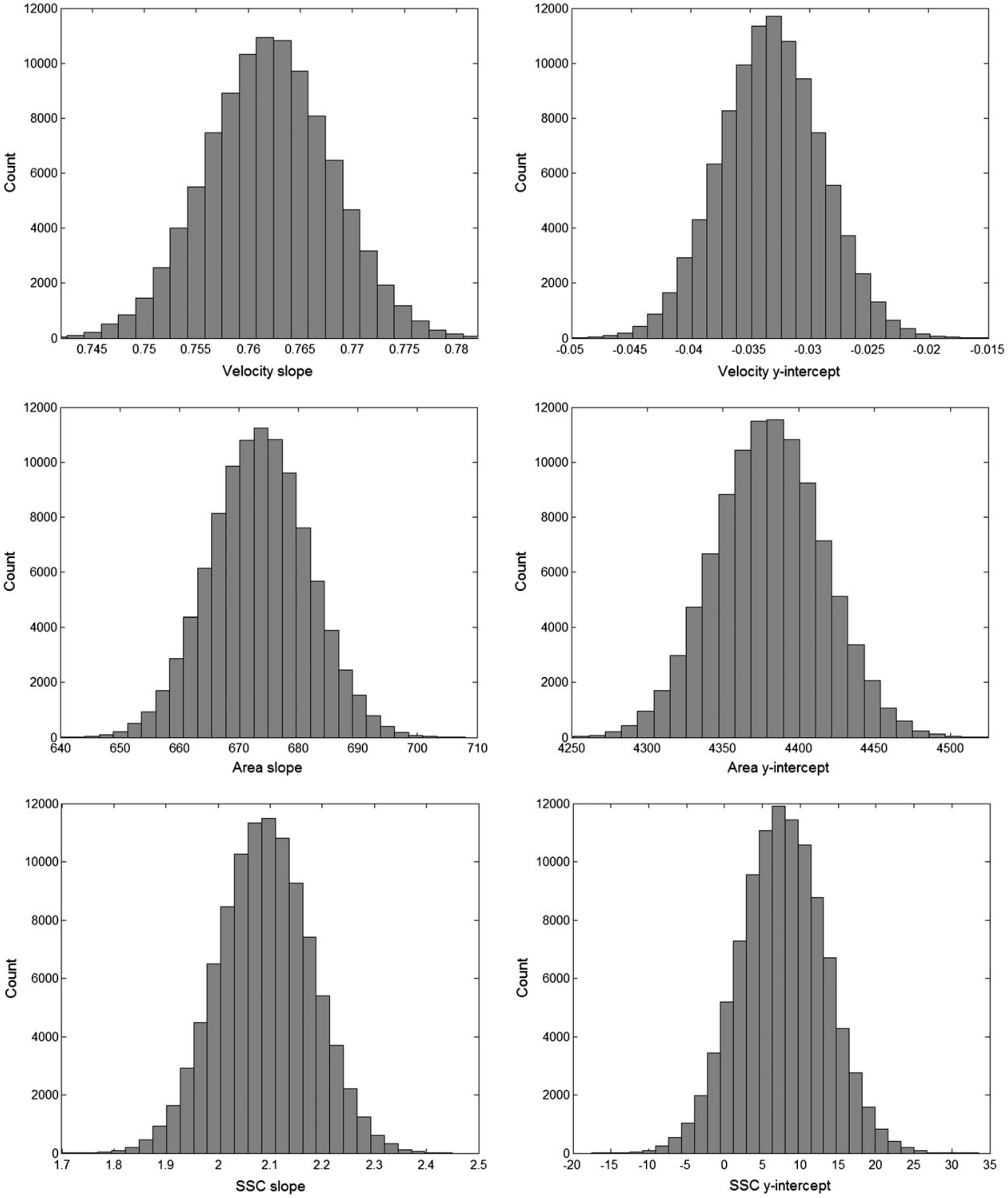

Fig. 5. Histograms of the slopes and y-intercepts from the Monte Carlo simulations for each of the instrument calibrations (Fig. 4, Eqs. 1–3).

means that correspond to the slopes and intercepts in Eqs. 1–3. The slope and intercept distributions were then used to simulate 100,000 realizations of the cross-section quantities, and thus, water discharge and SSF time series. In summary, direct application of Eqs. 1–3 provides only single time series of cross-section quantities, with unknown uncertainty, whereas the Monte Carlo approach provides probability distributions of the cross-section quantities. The mean time series from the Monte Carlo approach are equivalent to the direct application of Eqs. 1–3, and the distributions around the means represent the uncertainties.

Summation of the water discharge time series over the study period indicated that an imbalance existed in the discharge data between ebb and flood tide. Based on the mean water discharge time series from the Monte Carlo simulations, more water consistently traveled in the flood versus ebb direction during this time period (~6% of the total discharge in both directions). This imbalance cannot be fully explained by random error from the calibration residuals; even at 95% confidence, a slight imbalance still exists. Although the imbalance is relatively small as a percentage of the total discharge (6%), the volume of water that ebbs and floods over a tidal cycle is very large, such that the imbalance results in an unrealistic water budget for far south SFB. Comparison of the imbalance with long-term averages in water inputs (local tributaries and treatment plants) and precipitation and evaporation (Hager and Schemel, 1996) indicated that the imbalance could not be real, because it is an order of magnitude larger than the other elements of the water budget. Thus, the imbalance was removed by forcing a zero sum cumulative water discharge condition over 30-day periods (to span two spring–neap tidal cycles). This procedure ensures that sediment budget calculations are not affected by this bias in water discharge estimates and is only possible because of the tidal nature of the site and that the freshwater inflow to the reach is small relative to the water flux at Dumbarton.

3.3. Sediment budget

A simple sediment budget was calculated using a mass-balance approach:

$$\Delta S = \sum Q_{s\_\mathrm{Guadaulpe}} + \sum Q_{s\_\mathrm{Coyote}} + \sum Q_{s\_\mathrm{WWTP}} + \sum Q_{s\_\mathrm{Ungaged}} + \sum Q_{s\_\mathrm{Dumbarton}} \quad (4)$$

where ΔS is the change in sediment storage in far south SFB, and Q_s is the instantaneous (Dumbarton Bridge), daily (Guadalupe River and Coyote Creek), and annual average (estimated for the WWTP and ungaged watersheds) SSF at each location. For Coyote Creek, Guadalupe River, the ungaged tributaries and the WWTP, positive Q_s is bayward (downstream directed) into far south SFB. At the Dumbarton Bridge, positive Q_s is landward (flood-tide directed), and this direction represents a gain of suspended sediment to the far south SFB reach. Annual sediment budgets include only seasonal tributary fluxes, with the assumption that small dry-season tributary flows contribute a negligible flux of suspended sediment. Since the tributaries are only seasonally measured for SSC, a sediment budget using all three sites can only be computed for the wet season over the three year study. When a daily net flux is calculated (as in Fig. 9), the SSF at Dumbarton Bridge is tidally filtered prior to daily averaging to prevent aliasing of the data (Ruhl and Simpson, 2005). A low-pass Butterworth filter with a 30-hour stop and 40-hour pass period was used. Dumbarton flux data were not tidally filtered for seasonal or annual budget calculations, since the periods are long enough that the discrepancy between the daily and tidal periods is negligible.

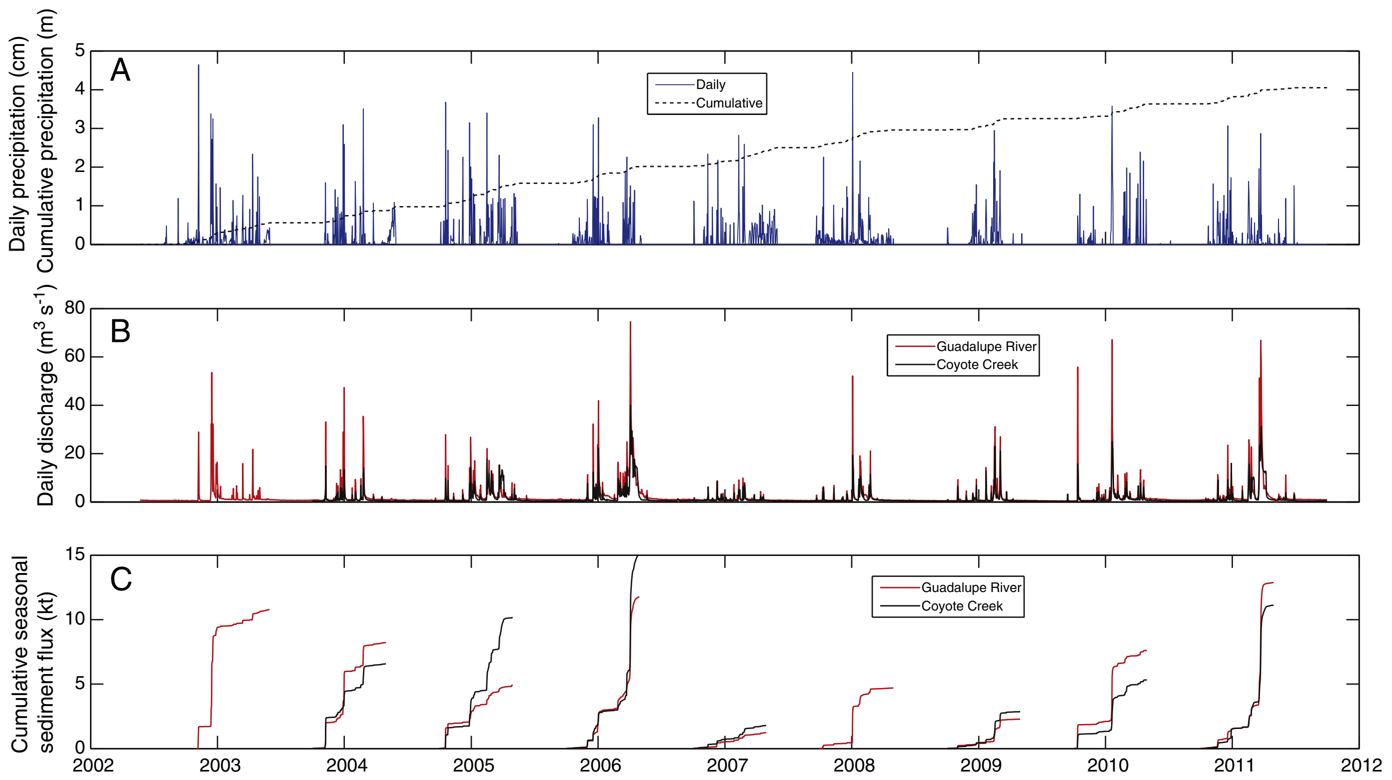

Fig. 6. Time series of A) Union City precipitation, Coyote Creek and Guadalupe River B) discharge, and C) cumulative suspended-sediment flux (in kilotonnes). Coyote Creek was not gaged for sediment in WY2003 or WY2008.

4. Results

4.1. Tributaries, precipitation, and wastewater

The daily precipitation as recorded at Union City, daily discharge, and seasonal, daily sediment flux in the Guadalupe River and Coyote Creek reported for 2002–2010 are shown in Fig. 6. In general, discharge in the two tributaries (Fig. 6B) responds to precipitation events (Fig. 6A), with a least-squares regression coefficient of determination $R^2 = 0.19$ ($n = 2923$, $p < 0.001$, Coyote Creek) and $R^2 = 0.34$ ($n = 3419$, $p < 0.001$, Guadalupe River; data not shown). There is minimal discharge during the low-flow summer period. That the relationship between precipitation and streamflow is only of moderate strength likely results from differences in the specific characteristics of the watersheds (e.g., slope, impervious surfaces, and elevation), locational differences between the precipitation station and the watersheds, and amount of antecedent precipitation. Daily SSF in the tributaries (Fig. 6C) responds to discharge, with a least-squares regression coefficient of determination $R^2 = 0.49$ ($n = 1273$, $p < 0.001$, Coyote Creek) and $R^2 = 0.70$ ($n = 1698$, $p < 0.001$, Guadalupe River; data not shown). The ungaged tributary discharge and SSF is 82% of the combined Guadalupe River and Coyote Creek values. Summary statistics on the tributary discharges and sediment fluxes are in Table 1. Annual precipitation and discharge increased each year between WY2009-2011.

All three WWTP have tertiary treatment. For San Jose/Santa Clara, the estimated mean annual discharge is 4.3 $m^3 s^{-1}$ for 2009–2011 (City of San Jose, 2012). Summer inputs exceed tributary inflow. The City of San Jose (2012) reported a discharge total suspended solids concentration average of 1.5 mg l^{-1} for 2009–2011. This produces an average estimate of 0.56 t d^{-1} sediment from the San Jose/Santa Clara WWTP to the reach. Hager and Schemel (1996) state that the San Jose/Santa Clara WWTP accounts for 72% of the WWTP discharge to far south SFB. Therefore, the estimated total SSF for the three WWTP is 0.78 t d^{-1}.

4.2. Dumbarton Bridge

Time series of instantaneous water discharge (corrected for the flood bias) and SSC_{xs} are shown in Fig. 7. The obvious variability in the discharge time series reflects the semidiurnal tidal cycle (ebb and flood) and the spring–neap tidal cycle, with larger discharges during the stronger spring tides than during the smaller neap tides. The SSC time series also shows variability on the spring–neap tidal time-scale. However, the highest SSC occurred in the spring of each year, roughly April–May, with peak concentrations occurring during the spring tides in this time period. These peak concentrations (400–1200 mg L^{-1}) are temporally decoupled from local precipitation and tributary discharge.

Suspended-sediment flux was computed from the corrected discharge time series (Fig. 7) and the distributions of slope and intercept for the turbidity — SSC_{xs} calibration (Fig. 5). Cumulative suspended-sediment flux time series (with uncertainty bounds) are shown for each Water Year of the study period in Fig. 8. The uncertainty bounds in Fig. 8 represent ± one standard deviation from the mean as determined from the Monte Carlo simulations. Statistics of the annual flux calculations are given in Table 2. The SSF at the Dumbarton Bridge (Fig. 8) exhibits a high degree of intra-and interannual variability. Within a Water Year, the majority of the annual flux occurs over a brief period in the spring (April–May), corresponding to the period when the SSC is high. The winter periods in WY2009–2010 generally show a slow flux of sediment into the reach, while all of WY2011exhibits fluxes that are primarily out of the reach. The strong springtime fluxes are bayward for WY2010–2011 but landward during WY2009 (and late spring in WY2010). The summer period for all Water Years shows minimal net flux. The net flux over these three Water Years is bayward.

4.3. Sediment budget

The sediment budget results are shown in Fig. 9 (daily) and Table 2 (seasonal and annual). The sediment budget is controlled primarily by the flux at Dumbarton, although seasonal tributary inputs were similar to the annual net flux at Dumbarton in WY2010. Overall, the tributary flux is <10% of the Dumbarton flux 95% of the time for the daily net flux (not shown). There is a high degree of variability in the daily net flux, mostly explained by Dumbarton flux variations. The high SSC periods in April and May each year correspond to the largest positive and negative peaks in the daily net flux. The cumulative net flux mirrors the flux record at Dumbarton and exhibits large interannual variability. The annual budget (Table 2) shows that this reach of SFB was likely depositional in WY2009, steady in WY2010, and erosional in WY2011. The balance over the three study years suggests that the reach lost about 145 kt of sediment.

5. Discussion

5.1. Uncertainty

Uncertainty estimates for sediment flux measurements are an important component of sediment budgets. Previous studies have used a variety of techniques to estimate uncertainty in sediment flux, such as assigning percentage errors to the measurements (Topping et al., 2000; Wright and Schoellhamer, 2005), as well as more complicated statistical approaches (Schmelter et al., 2011). Uncertainty is particularly important in tidal environments when the net sediment flux is of interest, because the net flux may be a small difference between two large fluxes that occur during ebb and flood tides. For example, the net

Table 1

Median (in bold) and interquartile range (in parentheses) of tributary discharge and suspended-sediment flux (SSF; in metric tons per day) for different periods. Precipitation values are the sum over the specified period. The period of record for Guadalupe River discharge is 23 May 2002–30 September 2011 and for Coyote Creek 1 October 2003–30 September 2011. The period of record for the suspended-sediment flux is winter only for WY 2003–2010 for Guadalupe River and WY2004-2007 plus WY2009–2010 for Coyote Creek. The 'Winter' period is defined as 1 October–30 April. The Union City precipitation record runs from 23 May 2002–30 September 2011. NA is used when data are not available.

	Guadalupe River		Coyote Creek		Ungaged tributaries		Union City
	Discharge ($m^3 s^{-1}$)	SSF ($t d^{-1}$)	Discharge ($m^3 s^{-1}$)	SSF ($t d^{-1}$)	Discharge ($m^3 s^{-1}$)	SSF ($t d^{-1}$)	Precipitation (mm)
Winter 2009	**0.68** (0.59–1.1)	**0.83** (0.60–1.3)	**0.51** (0.37–0.93)	**1.1** (0.79–2.3)	**1.0** (0.79–1.6)	**1.6** (1.2–2.8)	291
Winter 2010	**1.3** (0.59–2.1)	**1.4** (0.80–3.4)	**0.88** (0.45–1.7)	**1.3** (0.83–7.9)	**1.9** (0.94–3.0)	**2.1** (1.3–8.6)	378
Winter 2011	**1.4** (1.0–3.4)	**2.6** (1.4–10)	**0.91** (0.50–1.9)	**2.6** (1.2–12)	**1.8** (1.3–4.6)	**4.8** (2.2–19)	368
Period of record	**0.93** (0.68–1.3)	**1.5** (0.88–4.17)	**0.54** (0.42–0.85)	**1.9** (1.1–7.0)	**1.2** (0.93–1.8)	**2.9** (1.6–9.1)	4045
WY2009	**0.62** (0.51–0.76)	NA	**0.40** (0.31–0.57)	NA	**0.83** (0.67–1.0)	NA	294
WY2010	**1.1** (0.76–1.5)	NA	**0.51** (0.40–0.99)	NA	**1.3** (0.93–2.0)	NA	379
WY2011	**1.1** (0.99–1.7)	NA	**0.59** (0.45–1.1)	NA	**1.4** (1.2–2.3)	NA	417

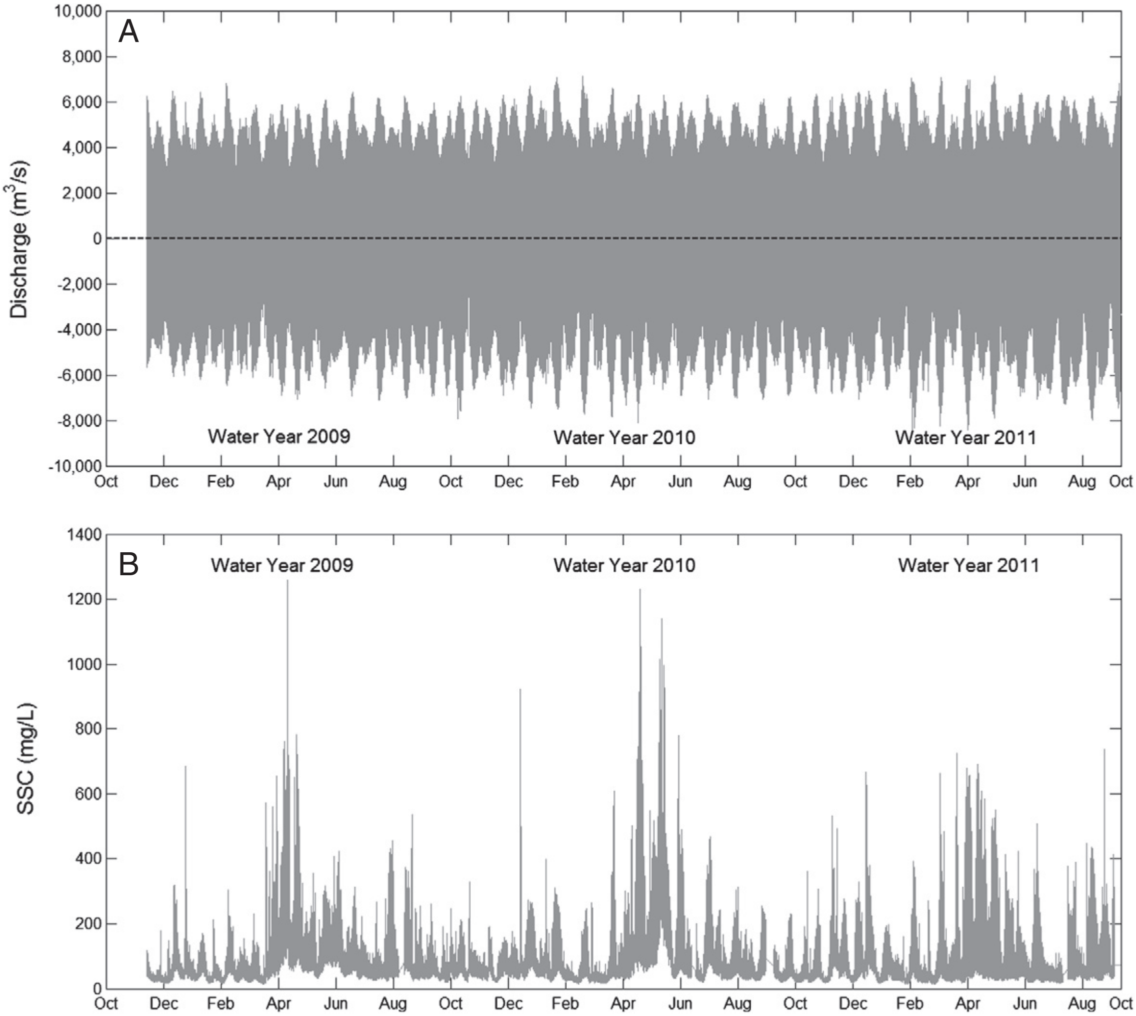

Fig. 7. Times series of data from the Dumbarton Bridge: A) water discharge and B) suspended-sediment concentration (SSC) for the Water Years listed. Positive discharge is bayward in the ebb tide direction.

sediment fluxes at Dumbarton Bridge were only 2%, 0.2%, and 13% of the total flux in either (ebb/flood) direction, respectively, for the three Water Years studied. Thus, small errors in the flux in either direction can compromise the ability to detect even the direction of the net flux.

Commonly, the most difficult component to estimate of an estuarine sediment budget is the sediment flux at the seaward boundary. For example, different estimates of net SSF through the mouth of the Humber Estuary do not agree on whether the direction of transport is landward or seaward (Tappin et al., 2003). Several studies estimate other components and use conservation of mass to estimate the flux at a seaward boundary but were unable to estimate uncertainty (Kirby, 1990; Hobbs et al., 1992; Eyre et al., 1998; Shi et al., 2003). McKergow et al. (2010) use SSC measurements and a numerical model to calculate flux at the seaward boundary of their study area and use an estimate of ungaged runoff to estimate that the flux error could be as high as ±20%. Squared errors of individual components can be summed to estimate the total error. Hossain and Eyre (2002) used cross-sectional sampling and a numerical model to estimate seaward SSF and estimated a ±12% error from summing squared errors for sediment sampling (±3% from coefficient of variation for 6 replicate samples), water flux measurement (±5%), and modeling error for seaward water exchange (±10%). The error associated with estimating cross sectionally-averaged SSC with the sediment samples was not considered. Wright and Schoellhamer (2005) used SSF estimates described in McKee et al. (2006) as the seaward flux in a sediment budget; components of flux uncertainty were daily averaging (±0.67%), water discharge (±5%), laboratory analysis of SSC (±5%), optical sensor calibration to SSC (±10%), and SSC heterogeneity in the cross section (±30%) for a total error of ±32%.

We chose a statistical approach to estimate uncertainty from random error, because the instrument calibrations provided the necessary information (i.e., regression residuals) to apply Monte Carlo simulations. It is important to note that this method only accounts for random errors in the measurements and calibrations; systematic biases in the measurements of the cross-section quantities (water discharge and SSC) are not accounted for, because these potential biases are unknown (it is impossible to know the true discharge or SSC). For the case of Dumbarton Bridge, we can estimate the systematic bias in the water discharge measurements, because they are constrained by a known water budget for far SFB; that is, the ebb and flood water discharges must balance over weekly to monthly time scales because this component dominates the water balance. This constraint was used to remove a persistent flood-directed bias in water discharge of about 6% of the total discharge. No such constraint exists for the sediment budget because flood and ebb directed sediment fluxes are not required to balance. Given the bias in water discharge, it is reasonable to expect some systematic (and unknown) bias in the SSC measurements as well. Thus, the uncertainty estimates presented herein for the sediment flux are likely lower bounds of the total uncertainty. However, even when only the random error is considered, Fig. 8 indicates that the uncertainty precludes knowing the direction of the annual sediment flux with a great deal of certainty.

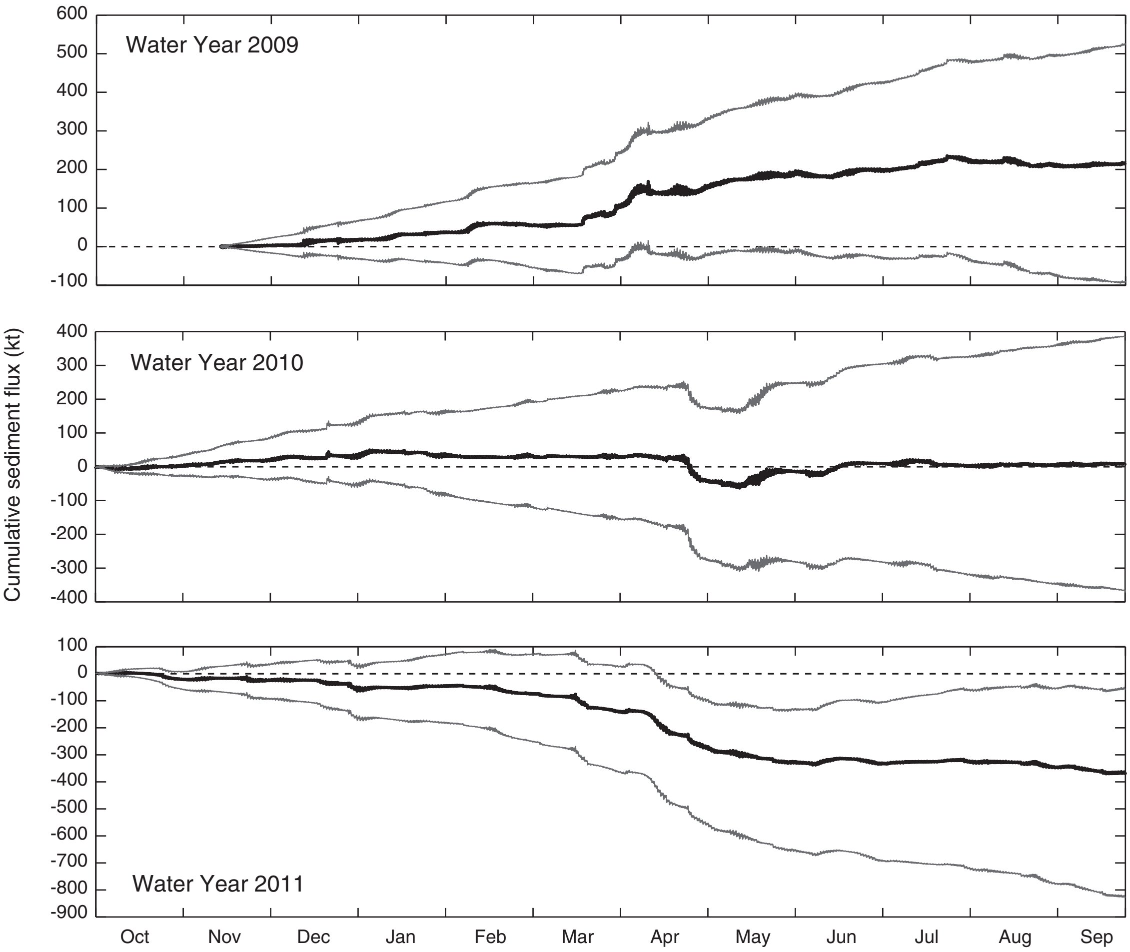

Fig. 8. Cumulative suspended-sediment flux at Dumbarton Bridge for the three Water Years. Solid black lines are the mean values from the Monte Carlo simulations; gray lines are ± one standard deviation. Positive values represent movement of sediment into the southern reach (flood tide directed).

The Monte Carlo simulations indicate that there is a 24%, 49%, and 87% chance that the Dumbarton flux is out of the reach for WY2009, WY2010, and WY2011, respectively. This means that, even given the large flux seen in WY2011, incorporating the uncertainty suggests that there is a 13% chance that the flux was in the direction opposite from what is reported. This reinforces the importance of constraining sediment budgets that are based on sediment transport measurements with independent measures of changes in sediment storage (e.g., repeat bathymetric surveys and sediment cores). This is particularly important for longer term sediment budgets because the errors in flux measurements accumulate over time.

Adopting the Monte Carlo approach provides a more statistically rigorous technique to quantifying the random error associated with measurements of this type. The 'sum of the individual errors' method common to sediment budget studies does provide some information about the error associated with the result, but there is generally no level of certainty provided for the error estimate: there is no certainty with the estimates of uncertainty. Although the uncertainties computed by the Monte Carlo approach are quite large (at least for this study), they provide an important level of confidence to our estimates of the suspended-sediment flux through Dumbarton Narrows.

5.2. Sediment supply

Conventional wisdom for SFB is that sediments are delivered to the bay during the wet season. They are then redistributed around

Table 2
Sediment budget analysis results for different periods. The flux values are in kilotonnes. Dumbarton flux values are the average sum (from the Monte Carlo results) over the period ± a confidence interval (CI), while the tributaries and WWTP display the sum over the period ± CI. The CI for Dumbarton is one standard deviation, ± 10% is assumed for the gaged tributaries and the WWTP, and ± 20% is assumed for the ungaged tributaries. The data are displayed first with the seasonal flux (where the time period corresponds to the seasonal tributary sediment data collection period), then with the annual flux. The tributary data are for the winter season only (1 October–30 April). The annual budget results use the annual Dumbarton data and the seasonal tributary data. Positive fluxes represent movement of sediment into the reach, while negative flux results represent a loss of sediment from the reach. NA is used when data are not available.

Period	Dumbarton flux (kt)	Gaged tributary flux (kt)	Ungaged tributary flux (kt)	WWTP flux (kt)	Net sediment flux (kt)	Deposition (+) or erosion (−, mm)
Winter 2009	140 ± 170	4.7 ± 0.47	3.9 ± 0.78	0.13 ± 0.026	150 ± 170	7.2 ± 8.1
Winter 2010	−23 ± 220	13 ± 1.3	11 ± 2.2	0.17 ± 0.034	1.2 ± 220	0.057 ± 10
Winter 2011	−310 ± 220	23 ± 2.3	19 ± 3.8	0.17 ± 0.034	−270 ± 220	−13 ± 10
WY2009	220 ± 310	NA	NA	0.25 ± 0.050	220 ± 310	11 ± 15
WY2010	11 ± 370	NA	NA	0.28 ± 0.056	35 ± 370	1.7 ± 18
WY2011	−440 ± 390	NA	NA	0.28 ± 0.056	−400 ± 390	−19 ± 19

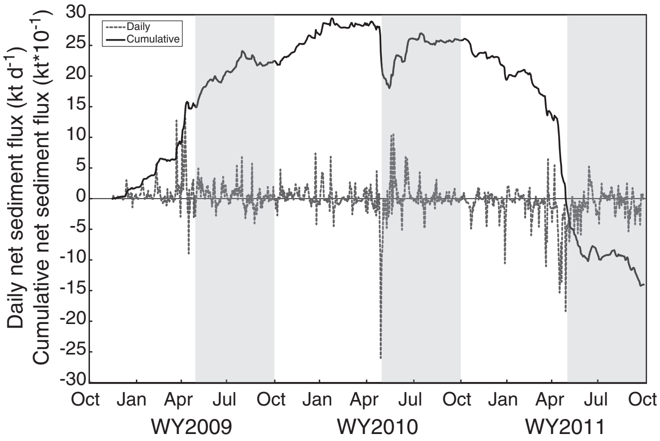

Fig. 9. Daily and cumulative net sediment flux for far south San Francisco Bay. Positive values increase sediment in the reach (flood tide directed). The shaded areas show when tributary sediment flux data are not available, and they do not contribute to the sediment budget.

the bay by wind waves generated over the extensive mudflats by strong, diurnal, summer winds (Conomos et al., 1985; Brand et al., 2010). However, at the Dumbarton Narrows, this may not hold. The data generally show sediment input during the wet season, but net fluxes in the channel are near zero during the windy summer period (Fig. 8). The periods of high springtime SSC are decoupled from the tributary inflow (Figs. 6 and 8), so the large increase in the suspended sediment in the water column is not coming directly from the tributaries. If the summer wind waves traveling over the extensive mudflats do lead to sediment redistribution, these sediments must be redistributed locally (e.g., from shoal to channel; Brand et al., 2010), without contributing to a flux through the Dumbarton Narrows.

To put the observed sediment flux into perspective of the far south SFB reach, we can estimate how much the annual sediment flux could contribute to deposition or erosion in the reach. Using seasonal and annual fluxes estimated for each of the three Water Years (Table 2), assuming a bulk density of 617 kg m^{-3} (an average bulk density from seven core samples collected in South San Francisco Bay during two different studies: Caffrey, 1995; Love et al., 2003), and an area for the reach of 34 km^2 at MTL (Hager and Schemel, 1996), basin-wide sediment deposition or erosion can be computed. During WY2009 and WY2010, the results suggest 11 ± 15 mm (mean ± standard deviation) and 1.7 ± 18 mm of deposition in the basin, respectively. For WY2011, the basin would have to supply 19 ± 19 mm of eroded sediments to account for the bayward SSF at Dumbarton Bridge (Table 2). This implies that, at least when the SSF is directed landward at the Dumbarton Bridge, the sediment supply is sufficient to allow marsh development to keep pace with mean sea level rise (measured to be 2.17 mm yr^{-1} at San Francisco; Flick et al., 2003) and potentially provide sediment to fill subsided areas.

One key question arises when looking at the Dumbarton Bridge data: what is controlling the direction of spring SSF? Longitudinal and vertical salinity gradients in South SFB lead to gravitational circulation. During wetter years, freshwater inflow coming into the northern estuary can create inverse estuarine conditions in South SFB, where water nearer the mouth of the estuary is fresher than the water at the Dumbarton Narrows. This leads to baroclinic residual flows and net fluxes of saltwater and sediment to the north (McCulloch et al., 1970; Walters et al., 1985). For the three water years we have data, the ranks of Sacramento–San Joaquin Delta flow into the northern estuary and seaward sediment flux at Dumbarton Bridge are identical. Additional years of data would enable testing a hypothesis that the two are related. Our salinity data are too sparse to estimate gravitational circulation during these Water Years, but we plan to incorporate these results with some hydrodynamic modeling results to confirm our hypothesis.

5.3. Implications for the South Bay Salt Pond Restoration Project

With the results from the sediment budget (Table 2), we can estimate the time to fill the subsided accommodation space in the project area using the data from the different Water Years to provide a range of times. The space will require between 18,000–28,000 kt of sediment, assuming 29–45 million m^3 of subsided space and a bulk density of 617 kg m^{-3}. Many wetland restoration projects require tributaries to deliver any needed sediments. Based on three years of data, the tributaries to this project area could provide enough sediment to fill the accommodation space in between 400 years (larger flux, smaller need) and 3300 years (smaller flux, larger need). However, since the flux past Dumbarton controls the net sediment flux for this reach, the tributaries play only a small role in the regional sediment supply to far south SFB. Using the results of the annual net sediment flux, the required sediment could be supplied in about 90–600 years using the WY2009 and WY2010 sediment budget results. The WY2011 results represent a loss of sediment from the reach and would not contribute to filling the accommodation space. These estimates really reflect the potential effects of long-term regional sediment supply assuming that there is no net loss of mudflats and marshes in the area and the accommodation space does not change due to sea level rise or construction. Regional sediment flux is not necessarily indicative of sediment deposition or erosion at a given location. Actual deposition rates in the ponds restored to tidal action are a function of water depth, the energy associated with tidal currents, and the difference between SSC of the water entering and leaving the site.

Sediments entering this reach of SFB from the rest of the bay are an important addition to the tributary sediment inputs, but this is true only in years when there is less freshwater entering the estuary during the springtime period of high SSC (e.g., WY2009). The three Water Years included in this study generally span the range of precipitation conditions in the region: WY2009 was a relatively dry year, WY2010 was an average year, and WY2011 was a relatively wet year. Since combined dry and average years (years when net SSF is from the bay into the reach) occur more frequently than wet years, we believe SFB serves as a net sediment source to the far southern reach over a long timeframe.

Given that the restoration project timeframe is on the order of 50 years, there likely will not be enough naturally supplied sediment to completely raise the elevation of all of the subsided areas to MTL during the expected timeframe of restoration. However, some of the subsided ponds may be maintained as managed ponds and not restored to tidal action, so the project may require less sediment overall than the estimate provided here. The sediment budget information is still quite useful to the restoration project managers, as it suggests that opening subsided ponds to tidal action may be most productive (in terms of regional sediment supply) during April and May of years with relatively low precipitation and freshwater inflow to the bay. In addition, since SFB is a larger supplier (or sink) of sediment than the local tributaries, the restoration project interactions with the rest of SFB are likely to be more important for sedimentation than the tributaries.

5.4. Future work

Studies relating to the SSF at Dumbarton Narrows are continuing. The high interannual variability in the SSF stresses the importance of long-term flux measurements in this dynamic environment. This will allow us to better understand the range of variability in the system and the relationship between net SSF and freshwater inflow to the bay. Also, additional analysis of existing data will help to understand the factors that control suspended-sediment flux on time-scales ranging from tidal to interannual. A key question is: what is controlling the spring sediment ‘bloom’ at the Dumbarton Narrows? SSC rise on the spring tide following the peak of the spring phytoplankton bloom in south SFB (data not shown). At present, this linkage is not understood, although there are several possible connections that we plan to explore with future work. One primary linkage could be phytoplankton cells contributing to the formation of biogenic flocs that can be detected with the turbidity sensor (Flory et al., 2004). A number of secondary linkages, where the phytoplankton bloom can generate other biophysical responses that can affect the stability of the mudflat sediments, must also be considered. Various studies have documented a number of potential mechanisms that can alter sediment stability, such as bioturbation by invertebrates (Palomo and Iribarne, 2000), invertebrate benthic grazing (Gerdol and Hughes, 1994), abiotic effects like subaerial exposure of the mudflat (Amos et al., 1988), the presence of benthic microalgae (Madsen et al., 1993), microbes (Lelieveld et al., 2003), and extracellular carbohydrates (de Deckere et al., 2002). With the extensive mudflats in this region, we must consider that several of these processes may be responsible for the results seen for far south SFB.

6. Conclusions

Measuring suspended-sediment flux continuously in a tidal estuary is fraught with challenges. Even with carefully collected field data, small suspended-sediment concentration differences between the large total mass that exchanges during flood and ebb tides lead to large uncertainties. Although our computed uncertainties on the sediment flux are large, several conclusions can be drawn from this study. The use of Monte Carlo simulations to quantify the random error associated with our estimates of SSF provides a valuable tool to predict uncertainty around our estimates. The SSF through the Dumbarton Narrows, the bayward margin of this reach of SFB, is generally an order of magnitude larger than the combined sediment flux from the two major tributaries in the reach, suggesting that the Dumbarton flux controls the sediment budget for far south SFB. The sediment budget results suggest that the direction and magnitude of the Dumbarton flux is linked to freshwater inflow to the bay. Although the tributaries will not deliver sufficient sediment to the project area to fill the subsided space on the time-scale of the restoration project, the proper timing of breaching events could take advantage of environmental conditions that promote landward sediment fluxes past the Dumbarton Bridge. In general, measurement of SSF at tidal cross sections enables calculation of sediment budgets for different compartments of an estuary. This may be particularly useful for evaluating current sediment budgets to anticipate the geomorphic evolution of shorelines and tidal marsh and the sustainability of proposed habitat restoration projects as sea level rises.

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