Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento–San Joaquin River Delta

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[1] Where rivers encounter estuaries, a transition zone develops where riverine and tidal processes both affect sediment transport processes. One such transition zone is the Sacramento–San Joaquin River Delta, a large, complex system where several rivers meet to form an estuary (San Francisco Bay). Herein we present the results of a detailed sediment budget for this river/estuary transitional system. The primary regional goal of the study was to measure sediment transport rates and pathways in the delta in support of ecosystem restoration efforts. In addition to achieving this regional goal, the study has produced general methods to collect, edit, and analyze (including error analysis) sediment transport data at the interface of rivers and estuaries. Estimating sediment budgets for these systems is difficult because of the mixed nature of riverine versus tidal transport processes, the different timescales of transport in fluvial and tidal environments, and the sheer complexity and size of systems such as the Sacramento–San Joaquin River Delta. Sediment budgets also require error estimates in order to assess whether differences in inflows and outflows, which could be small compared to overall fluxes, are indeed distinguishable from zero. Over the 4 year period of this study, water years 1999–2002, 6.6 ± 0.9 Mt of sediment entered the delta and 2.2 ± 0.7 Mt exited, resulting in 4.4 ± 1.1 Mt (67 ± 17%) of deposition. The estimated deposition rate corresponding to this mass of sediment compares favorably with measured inorganic sediment accumulation on vegetated wetlands in the delta.

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1. Introduction

[2] Conceptually, where a river transitions to become an estuary, the energy available to transport suspended sediment decreases. The slope of the channel decreases and the influence of tidal backwater increases as the strength of the tidal signal increases. At some point, the tidal signal will become strong enough to cause periodic slack tide and flow reversal. Measurement of water discharge and sediment flux in this transitional region is difficult because their magnitude and direction can vary at the timescales of both tides and river discharge. Slack tide is of particular importance for suspended-sediment transport because it is likely the first time a river parcel of water has no turbulent energy to suspend sediment, favoring deposition and often creating a delta. Deposition of riverine sediment may sustain deltaic wetlands against sea level rise and subsidence [*Pont et al.*, 2002].

[3] Other factors also favor deposition where a river becomes an estuary. In tidal freshwater channels, tidal pumping associated with the fortnightly spring/neap tidal cycle periodically can prevent downstream transport of riverine sediment and cause deposition [*Guezennec et al.*, 1999]. Exopolymer secretions by bacteria and microalgae enhance aggregation and deposition of fine sediment where freshwater begins to mix with saltwater [*Decho*, 1990; *Eisma*, 1986; *Wolanski et al.*, 2003].

[4] The magnitude of the riverine signal (or river discharge) relative to the tidal signal determines the location, magnitude, and grain size of sediment deposition at the riverine/estuarine transition. Reductions in river discharge caused by dams and water withdrawal can increase tidal pumping, reduce scour, and increase deposition [*Wolanski et al.*, 2001], decrease riverine sediment supply and deposition [*Yang et al.*, 2003], or shift deposition landward and erode the seaward delta [*Jay and Simenstad*, 1996]. Deposition of fine sediment can be shifted seaward, converting bottom sediments from coarse to fine, by reduction of estuarine volume by dikes that make the estuary more riverine [*Lesourd et al.*, 2001]. Thus deposition that builds deltas and wetlands in estuaries is dependent on the balance between the river signal propagating down from the watershed and the tidal signal propagating up from the ocean.

[5] The purpose of this paper is to (1) describe methods for estimating sediment budgets (and errors) at the interface

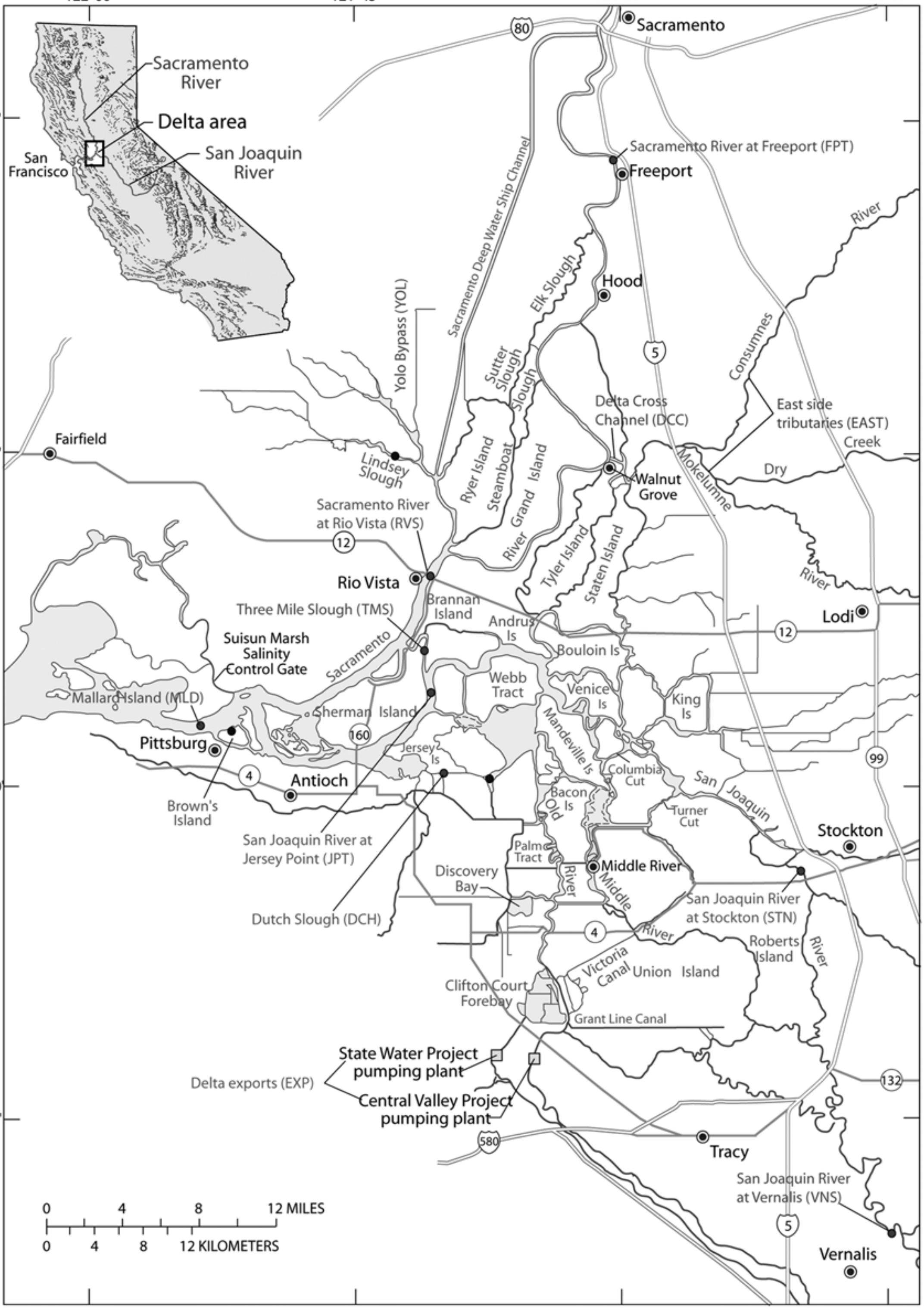

Figure 1. Sacramento–San Joaquin River Delta channel network. Red circles indicate suspended-sediment monitoring locations. Brown circles are locations of inorganic sediment accumulation measurements at natural vegetated wetlands by *Reed* [2002]. See color version of this figure in the HTML.

between rivers and estuaries and (2) apply the methodology to the Sacramento-San Joaquin River Delta where several rivers merge and become the San Francisco Bay estuary (Figure 1). The mixed nature of the sediment transport processes (riverine versus tidal), timescale of changes in flow and transport (multiweek high river flows versus subdaily tidal variations), and complexity and size of the delta (several inflows and cross-delta transport pathways) make quantification of the sediment budget an ambitious effort. Further, because the goal of a sediment budget is generally to compare inflows to outflows and deduce deposition or erosion, a detailed error analysis is required in order to asses whether this difference, which could be small compared to the overall fluxes, is distinguishable from zero. Any monitoring program to quantify sediment budgets at the river/estuary interface must address these difficulties.

[6] In 1998, instrumentation was installed (described in detail in subsequent sections) to continuously monitor suspended-sediment flux at several key sites throughout the delta, with the goal of quantifying the suspended-sediment budget in support of ongoing ecosystem restoration efforts. We describe the methods for data collection and editing, procedures for decomposing these records into riverine and tidal components, a detailed error analysis of the sediment flux estimates, and the development of daily suspended-sediment flux records. All of these methods and analysis techniques, and in particular the error analysis, have broad relevance for other researchers attempting to quantify suspended-sediment transport at the interface between rivers and estuaries. We also present the results of the sediment budget for the delta, which has implications for regional ecosystem restoration efforts, as described below.

[7] A sediment budget provides a quantitative framework for understanding sediment sources, sinks, deposition, and erosion. For sediment-associated constituents, a sediment budget is needed to develop a constituent budget [*Tappin et al.*, 2003]. The principle of conservation of mass requires that sources and sinks balance and is used either to estimate a component that is difficult to measure, such as net sedimentation [*Hossain and Eyre*, 2002] or ocean exchange [*Eyre et al.*, 1998; *Hobbs et al.*, 1992], or to check that estimates of the various components are reasonable [*Schubel and Carter*, 1976; *Yarbro et al.*, 1983]. In this study, we measure sediment inflow and outflow and use conservation of mass to estimate net deposition, which we compare to independent point measurements of inorganic sediment accumulation on vegetated wetlands.

[8] The mission of the California Bay-Delta Authority is to develop and implement a long-term comprehensive plan that will restore ecological health and improve water management of San Francisco Bay and the delta. This plan may include the restoration of tidal action to delta islands with the goal of restoring naturally functioning tidal wetlands. Tidal wetlands require a source of suspended sediment, particularly if the restored areas have subsided significantly. Thus effective restoration planning in the delta requires knowledge of the suspended-sediment budget and transport pathways of the delta.

2. Data Collection

[9] The Sacramento River drains the northern part of California's Central Valley, an area of approximately 60,900 km^2, including the drainage basins of the Feather and American rivers. The San Joaquin River drains approximately 35,060 km^2 in the southern Central Valley. The Cosumnes and Mokelumne rivers enter the delta directly from the east, draining areas of approximately 1900 and 1700 km^2, respectively. River discharge is greatest during winter and spring and smallest during the dry summer and early autumn. Tides propagate into most of the delta when river discharge is small. Suisun Bay is the subembayment of San Francisco Bay that is seaward of the delta. Tides in Suisun Bay are mixed diurnal and semidiurnal and the tidal range varies from about 0.6 m during the weakest neap tides to 1.8 m during the strongest spring tides. Most of the waters of the delta are fresh and during the dry season flow from reservoirs is managed to try to maintain a salinity of 2 parts per thousand in Suisun Bay.

[10] At the confluence of the four rivers, a complex network of natural and man-made channels has developed (Figure 1). The Sacramento San Joaquin Delta Atlas [*California Department of Water Resources*, 1995] contains detailed information on the history of the delta; a brief summary is provided here. Levee construction and draining of marshlands began in late 1850. As a result, the delta today consists of a network of slough channels surrounding former marshlands commonly termed "islands" which are primarily used for agriculture. Because of this channelization, only 0.02 km^2 of nonvegetated tidal flats exist in the delta today [*California Department of Fish and Game*, 1997]. Also, because of the high organic content of delta soils, draining of marshes has resulted in significant land subsidence such that most of the islands are currently below mean sea level, some by as much as 4 m. The delta also contains the pumping facilities that move State Water Project and Central Valley Project water to southern California.

[11] In July of 1998 the U.S. Geological Survey (USGS) installed five optical backscatter sensors within the delta in order to continuously monitor suspended-sediment concentration and flux. The five locations are shown on Figure 1 and are as follows: (1) Sacramento River at Freeport (FPT), (2) Sacramento River at Rio Vista (RVS), (3) San Joaquin River at Stockton (STN), (4) San Joaquin River at Jersey Point (JPT), and (5) Three Mile Slough (TMS), which connects the Sacramento and San Joaquin rivers within the delta. These sites were chosen in order to monitor the inflow of sediment to the delta and transport through the major pathway between the Sacramento and San Joaquin rivers (outflow has been monitored through a separate initiative). Several other sites are indicated on Figure 1 that will be referred to throughout the paper, including the San Joaquin River near Vernalis (VNS) which has been the location of a USGS daily sediment station since 1957, Dutch Slough (DCH) at which flow rate was measured, and Mallard Island (MLD) which is here considered the downstream boundary of the delta, and has an available daily suspended-sediment record since 1994 [*McKee et al.*, 2002].

[12] Continuous measurements of suspended-sediment flux at each of the sampling locations consisted of the following components: (1) measurement of optical backscatter (OBS) near the bank at 15 min intervals, (2) periodic (approximately monthly) measurements of discharge-weighted, cross-sectional average, suspended sediment concentration (SSC_{xs}) and point suspended-sediment concentration at the sensor (SSC_{pt}), and (3) measurements of flow rate (Q) at 15 min intervals (except for Freeport, where the interval was 1 hour).

2.1. Optical Backscatter (OBS) Measurements

[13] Optical backscatter sensors transmit a pulse of infrared light through an optical window [*Downing et al.*, 1981]. The light is scattered, or reflected, by particles in front of

Table 1. Characteristics of Measurements and Calibration Details for the Five Optical Sensor Sites

	Characteristics of SSC Measurements										
	SSC_{xs}		SSC_{pt}		Percent Good Data		Equation (1) Parameters		Optical Sensor Calibration Equations[b]		
Site[a]	Data Points	Maximum, mg/L	Data Points	Maximum, mg/L	OBS, %	Flow, %	α	β	Data Points	Equation	R^2
FPT	88	152	61	105	52	98	0.38	−0.61	48	$SSC_{xs} = 0.45OBS - 3.2$	0.83
RVS	47	173	82	113	45	98	0.25	−0.78	45	$SSC_{xs} = 0.31OBS - 6.2$	0.65
TMS	40	86	73	137	53	80	0.26	−0.57	38	$SSC_{xs} = 0.27OBS$	0.80
STN	47	254	77	217	20	91	0.43	−0.58	45	$SSC_{xs} = 0.37OBS + 9.8$	0.60
JPT	44	46	90	67	74	90	0.26	−0.49	42	$SSC_{xs} = 0.21OBS + 7.1$	0.50

[a]FPT, Sacramento River at Freeport; RVS, Sacramento River at Jersey Point; TMS, Three Mile Slough; STN, San Joaquin River at Stockton; JPT, San Joaquin River at Jersey Point.

[b]SSC_{xs} in mg/L, OBS in mV; all p values < 0.001 for an F test of SSC_{xs} versus OBS.

the window to a distance of about 10–20 cm at angles of as much as 165°. Some of this scattered, or reflected, light is returned to the optical window where a receiver converts the backscattered light to a voltage output. The voltage output (OBS) is proportional to suspended-sediment concentration (at the location of the sensor) if the particle size and optical properties of the sediment remain fairly constant. This calibration will vary according to the size and optical properties of the suspended-sediment. Also, it was desired here to use the backscatter at a single point (near the channel bank for all sites) to represent the cross-sectional average concentration (SSC_{xs}). This may confound calibration if large lateral or vertical concentration gradients are present. Therefore the sensors must be calibrated either in the field or a laboratory using suspended material from the field. Finally, if the optical window is fouled by biological growth or debris, the sensor output is invalid. OBS-3 sensors, manufactured by D & A Instruments Co. (use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey), were deployed at the five sites in July 1998. The sensors were programmed to sample once per second (1 Hz) over a 1 min time period every 5 min, then average over each 15 min time period. This is the same sampling scheme as used to measure water discharge at the sites.

2.2. Suspended-Sediment Concentration (SSC) Measurements

[14] Discharge-weighted, cross-sectional average, suspended-sediment concentration (SSC_{xs}) was measured periodically using the equal discharge increment (EDI) method and standard samplers. The EDI method entails depth-integrated, isokinetic sampling at several locations across the channel representing the centroids of equal discharge increments. At the Sacramento River at Freeport site, several measurements of SSC_{xs} were made using the equal width increment method and these data were included in the calibration described in the following section. Details of sediment sampling procedures are given by *Edwards and Glysson* [1999]. Also at the time of EDI measurements, water samples were collected at the sensor location (SSC_{pt}) using a van Dorn sampler in order to compare the concentration at the sensor location with the cross-sectional averaged concentration. Laboratory methods used to determine concentration and grain size are described by *Guy* [1969]. The number of measurements and maximum concentrations for each site are given in Table 1 (characteristics of SSC measurements).

2.3. Flow Measurements

[15] Flow was monitored at 15 min intervals by continuously measuring an index velocity with an ultrasonic velocity meter (UVM) [*Ruhl and Simpson*, 2005]. A calibration was then developed for each site between the index velocity and the cross-sectional average velocity, measured periodically with an acoustic Doppler current profiler (ADCP). Stage was also monitored and related to the cross-sectional area, which when multiplied by the cross-sectional average velocity provided the discharge.

3. Optical Sensor Calibrations

3.1. Biological Fouling

[16] Fouling of the OBS sensor can occur due to biological growth on the optical window, resulting in voltage readings not representative of the suspended-sediment concentration. The sensors were cleaned approximately monthly at the times of SSC measurements. For each of the sensors, the voltage records were examined and all data was removed for periods of perceived sensor fouling. As an example, Figure 2 shows the raw and edited OBS voltage records for the Sacramento River at Rio Vista. Periods of fouling are apparent in Figure 2 when voltage response increases exponentially in the absence of changes in sediment concentration, followed by cleaning of the optical window which brings the voltage down to prefouling levels. Table 1 (percent good data columns) summarizes the degree of fouling at each site by presenting the percentage of nonfouled (i.e., good) data for the entire record. Table 1 also contains the percent of good data for the flow measurements, which may be compromised by equipment malfunction instead of biological fouling.

3.2. Sensor Drift

[17] Initial analysis of the OBS records and the relationship between OBS and SSC indicated that the sensor output was drifting with time. This tendency was found for all five sites. An example of this drift is illustrated in Figure 3, which shows the ratio of OBS to point concentration at the sensor (SSC_{pt}) for Three Mile Slough. If sediment concentration were proportional to optical backscatter, this ratio would be constant in time (with some scatter). The

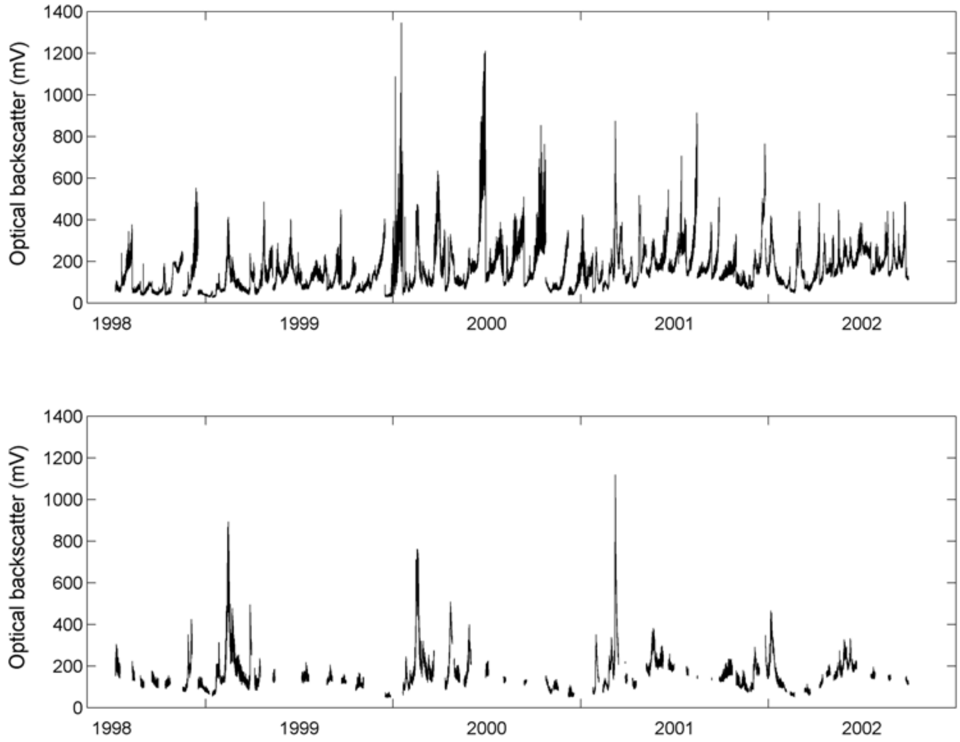

Figure 2. (top) Raw and (bottom) edited optical backscatter records for the Sacramento River at Rio Vista.

decrease in the ratio with time indicates that, for the same concentration, the sensor returned a higher voltage in 2001 than in 1998, for example. The precise reason for the drift is unknown, but it is thought to be the result of wear and tear on the sensors. Other factors were investigated, such as particle size, salinity, and water temperature, but none could be positively identified as the cause of the drift. Particle size, in particular, is known to have a significant effect on the relationship between concentration and optical backscatter [*Sutherland et al.*, 2000; *Conner and De Visser*, 1992]. For each water sample taken, sand/silt splits were determined which provides some indication of the particle size in suspension. However, as shown by *Wright* [2003] at the Three Mile Slough site, significant aggregation and disaggregation may take place over a tidal cycle. Since the samples become disaggregated prior to being analyzed for concentration and grain size, the in situ particle size distribution of the samples is unknown. Therefore it is impossible to rule out particle size changes as the cause of the drift. For this to be the case, the mechanisms controlling flocculation would have to be changing is such a way that the mean particle size has been decreasing systematically with time over the period of record presented here.

[18] Because the cause of the drift is unknown, a simple, nonphysically based approach was used to remove the drift from the records. F tests of SSC_{pt}/OBS versus time indicated p values less than 0.001 for all sites. The drift was removed from the original OBS voltage records using the following equation:

$$\frac{SSC_{pt}}{OBS} = \alpha\left(\frac{t}{T}\right)^{\beta} \tag{1}$$

where t is time in days, T is the total time of the period of record, and the exponents α and β are given in Table 1 (equation (1) parameters columns) for each site. The adjusted voltage records were then computed from:

$$\frac{OBS_{new}}{OBS} = \left(\frac{t}{T}\right)^{\beta} \tag{2}$$

3.3. Relation Between SSC_{xs} and OBS

[19] Calibrations were developed directly between the cross-sectional average concentration, SSC_{xs}, and point

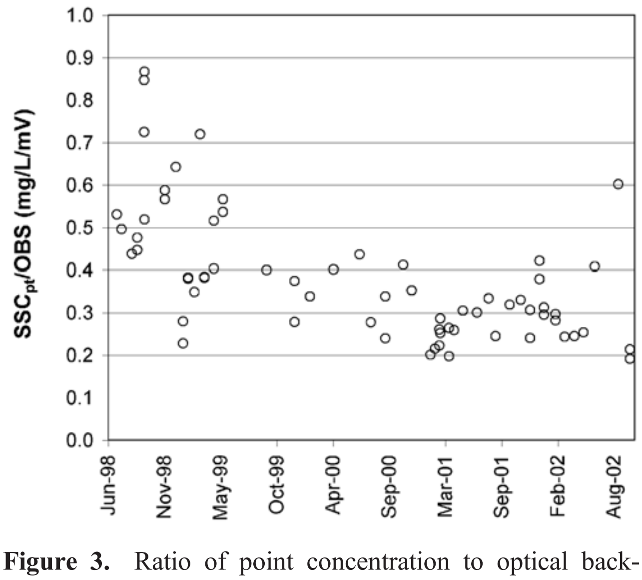

Figure 3. Ratio of point concentration to optical backscatter for Three Mile Slough, illustrating the drift in sensor voltage output with time.

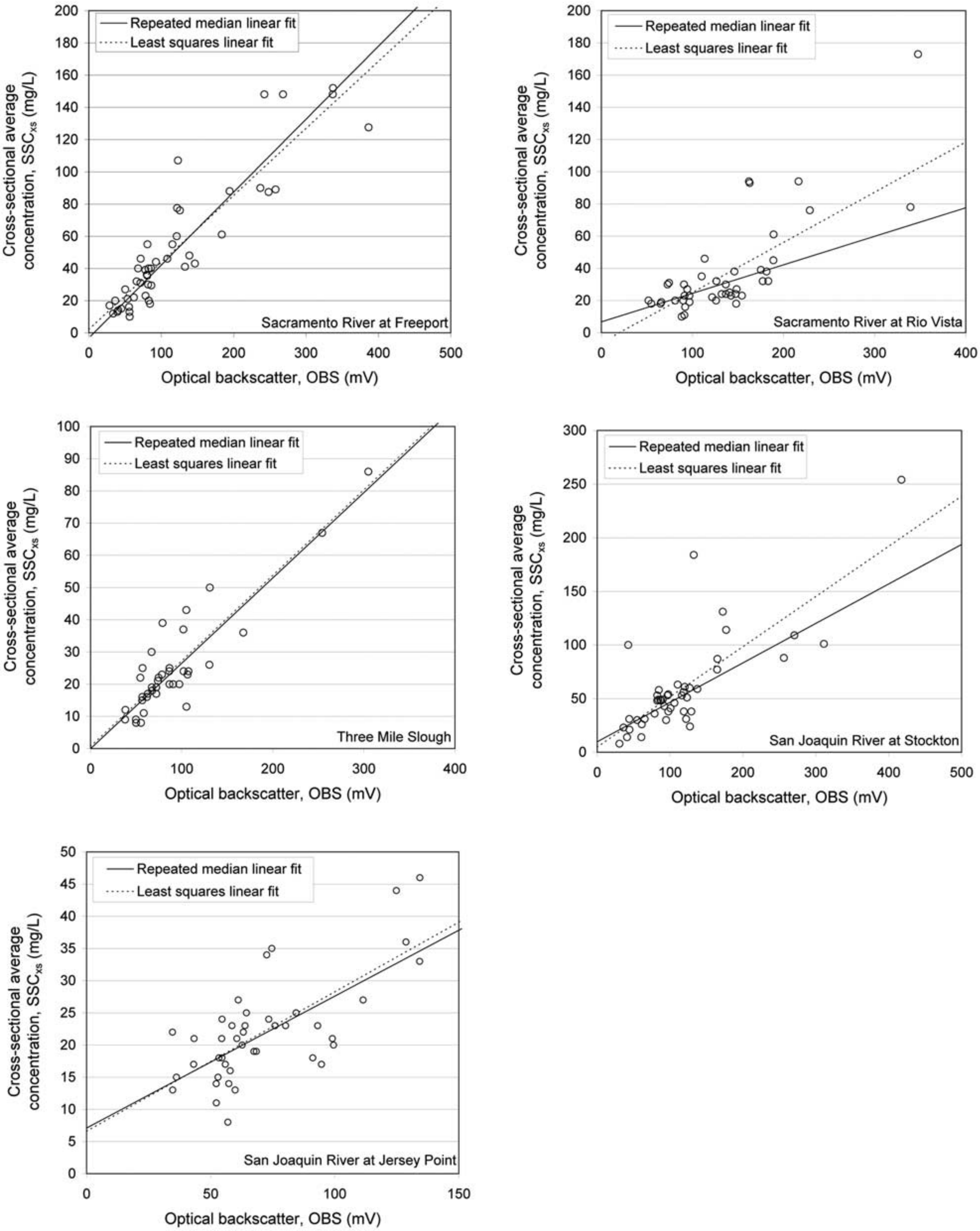

Figure 4. Relation between cross-sectional average concentration, SSC_{xs}, and near-bank optical backscatter, OBS, for the five delta sites.

optical backscatter corrected for drift, OBS. We assume that a stable relation between OBS and SSC_{xs} exists and we will evaluate this assumption as part of an error analysis. Two methods for linear regression were applied: (1) standard least squares and (2) the nonparametric repeated median method [*Helsel and Hirsch*, 1992; *Buchanan and Ganju*, 2002]. The repeated median method tends to ignore outlying points by selecting the median of the slopes between all

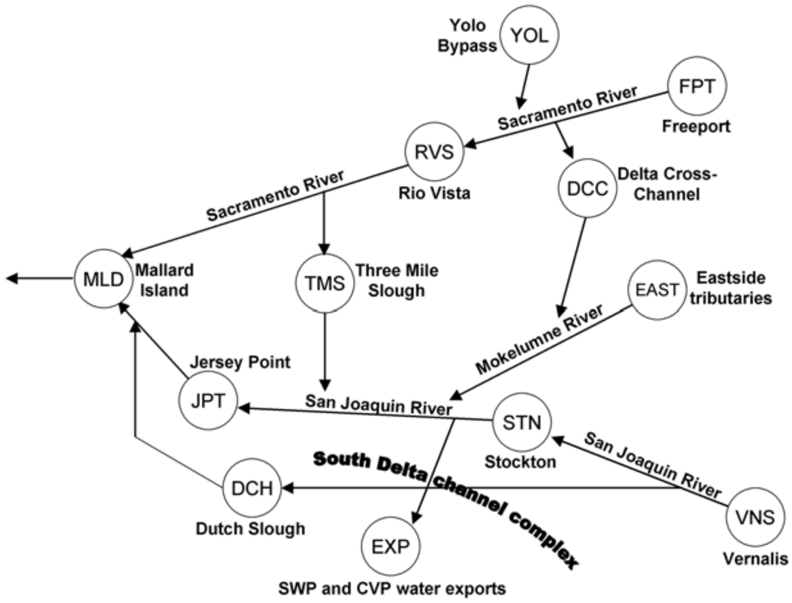

Figure 5. Schematic diagram of sediment pathways in the delta.

point pairs. Figure 4 shows the data and linear fits by both methods for each site. The site with greatest difference between the two methods is the Sacramento River at Rio Vista. At this site, the repeated median method tends to ignore the highest concentration points resulting in a significantly smaller slope than for least squares. These high concentration points all occurred during relatively high flow in the Sacramento River and flow from the Yolo Bypass which join 3 km upstream. When SSC_{xs} was large, cross-sectional variability was large because SSC at the OBS on the northwestern bank is relatively small (data not shown). Incomplete lateral mixing at high flow appears to change the relation between OBS and SSC_{xs} at Rio Vista. Thus these data points are not erroneous but indicate that our assumption of a stable relation between OBS and SSC_{xs} is poor at Rio Vista. Rather than exclude these data points by applying the repeated median method, the least squares method was selected for Rio Vista, while for all other sites the repeated median method was used. The calibration equations are summarized in Table 1 (optical sensor calibration equations columns). These equations were used to develop 15 min SSC_{xs} records which were multiplied by the 15 min flow records resulting in 15 min records of suspended-sediment flux at each location.

4. Sediment Budgets

[20] The main sediment pathways within the delta are shown in Figure 5 (also refer to Figure 1). Sediment enters the delta from the Sacramento River at Freeport (FPT), Yolo Bypass (YOL), San Joaquin River near Vernalis (VNS), and various eastside streams including the Cosumnes and Mokelumne rivers (EAST). Significant redistribution may occur within the delta through Georgiana Slough and the Delta Cross Channel (DCC), a gated diversion channel that moves water from the north to the south delta (from Sacramento River to Mokelumne River). Three Mile Slough (TMS) also provides a connection between the Sacramento and San Joaquin rivers. Water is exported from the southern delta to southern California through State Water Project and Central Valley Project pumping facilities (EXP). Sediment exits the delta just downstream from the Sacramento–San Joaquin confluence near Mallard Island (MLD).

[21] The goal of the sediment budget analysis was to develop continuous, daily flow and suspended-sediment records for each of the sites identified in Figure 5, which could then be used to quantify the annual water and sediment budgets for the four water years with optical sensor data (1999–2002). Since optical backscatter data was only available for six of the sites, various other data sources were used to develop daily records as discussed in the following section and summarized in Table 2.

4.1. Development of Daily Records

[22] The Sacramento River at Freeport (FPT) is the site of a USGS daily suspended-sediment station (11447650) as well as an OBS sensor and thus provides a good test of the OBS technology for measuring suspended-sediment flux. Details of USGS data collection procedures and daily sediment record development are given by *Edwards and Glysson* [1999] and *Porterfield* [1972]; the daily records are published in the USGS annual data reports (U.S. Geological Survey, water resources data for California, 1999–2002). This is also an important site because previous studies [e.g., *Porterfield*, 1980] have suggested that the Sacramento River delivers the majority of sediment to the delta. For comparison with the USGS daily station records, the OBS-derived suspended-sediment concentrations were averaged for each day. The comparison is plotted in Figure 6, and the agreement is seen to be quite good [*Schoellhamer and Wright*, 2003]. Thus, for the purposes of the sediment budget the USGS daily station record (flow and sediment) is used because it is continuous (i.e., no gaps due to biological fouling). The error of the daily sediment record is 15% (U.S. Geological Survey, Sediment station analysis, station 11447650, Sacramento River at Freeport, California, unpublished data, 2003). The San Joaquin River at Vernalis (VNS) is also the site of a USGS daily suspended-sediment

Table 2. Summary of Daily Record Data Sources and Methods

Site	Daily Record Data Sources and Methods
Sacramento River at Freeport (FPT)	USGS daily flow and sediment station (11447650)
San Joaquin River at Vernalis (VNS)	USGS daily flow and sediment station (11303500)
Sacramento River at Rio Vista (RVS)	OBS-derived flux record, filled with rating curve; UVM flow record, filled with DAYFLOW (DAYFLOW program description, http://www.iep.water.ca.gov/DAYFLOW).
San Joaquin River at Stockton (STN)	OBS-derived flux record, filled with rating curve; UVM flow record, filled with correlation with Vernalis flows
San Joaquin River at Jersey Point (JPT)	OBS-derived flux record, filled with rating curve; UVM flow record, filled with DAYFLOW
Three Mile Slough (TMS)	OBS-derived flux record, filled with rating curve. UVM flow record, gaps not filled
Mallard Island (MLD)	flows from DAYFLOW; sediment fluxes from *McKee et al.* [2002]
Yolo Bypass (YOL)	flows from DAYFLOW; sediment fluxes from rating curve using data from 1957–1961, 1980
East side tributaries (EAST)	flows from DAYFLOW; Cosumnes and Mokelumne sediment fluxes from rating curves using data from 1965–2002
Delta Cross Channel and Georgiana Slough (DCC)	flows from DAYFLOW; no sediment data
Dutch Slough (DCH)	daily UVM flow record, gaps (7% of record) filled with mean value; sediment time series in water year 2000 not reliable
Delta exports (EXP)	flows from DAYFLOW; sediment flux assumed to be zero

station (11303500), and these are the records used for both flow and sediment. There is not an OBS sensor at this site. The error of the daily sediment record is 10% (U.S. Geological Survey, Sediment station analysis, station 11303500, San Joaquin river at Vernalis, California, unpublished data, 2003).

[23] For the remaining OBS sensor sites (see Table 1), the 15 min flow and OBS-derived suspended-sediment flux records were averaged for each day to obtain the daily records. To construct continuous records, however, the periods of missing data (gaps) had to be estimated. For the flow records this was accomplished through various means. For the Sacramento River at Rio Vista (RVS) and San Joaquin River at Jersey Point (JPT), which were missing approximately 2% and 10% of the flow data respectively, the missing values were estimated using results from the California Department of Water Resources DAYFLOW program (Interagency Ecological Program,

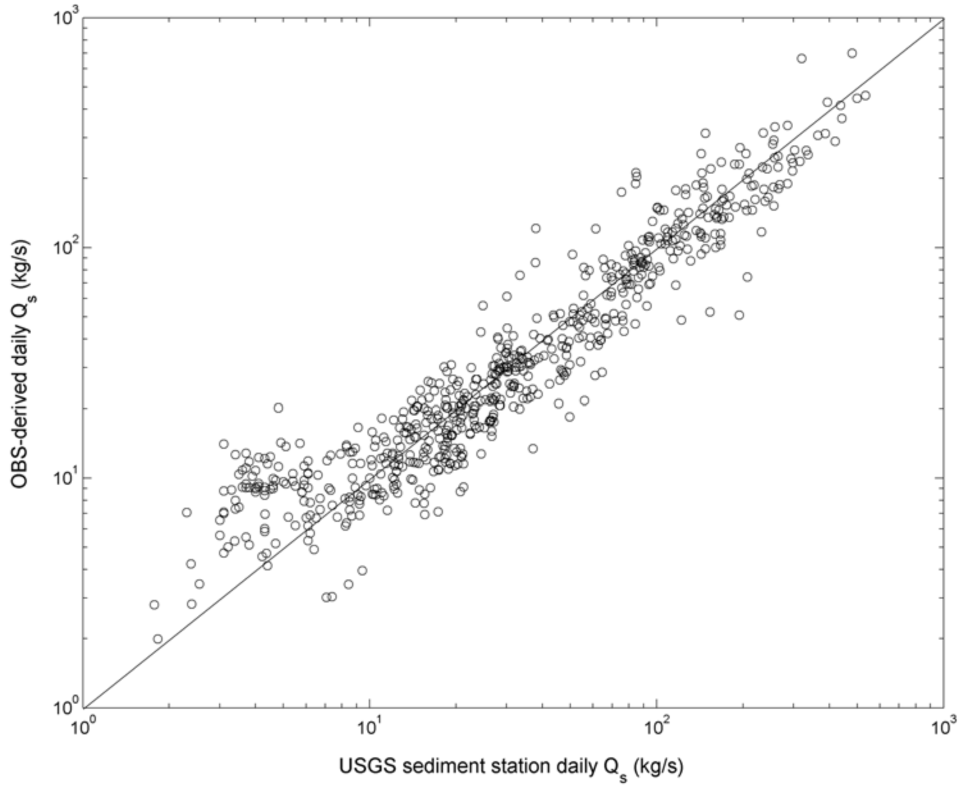

Figure 6. Comparison of OBS-derived and USGS sediment station daily suspended-sediment flux (Q_s) for the Sacramento River at Freeport for water years 1999–2002.

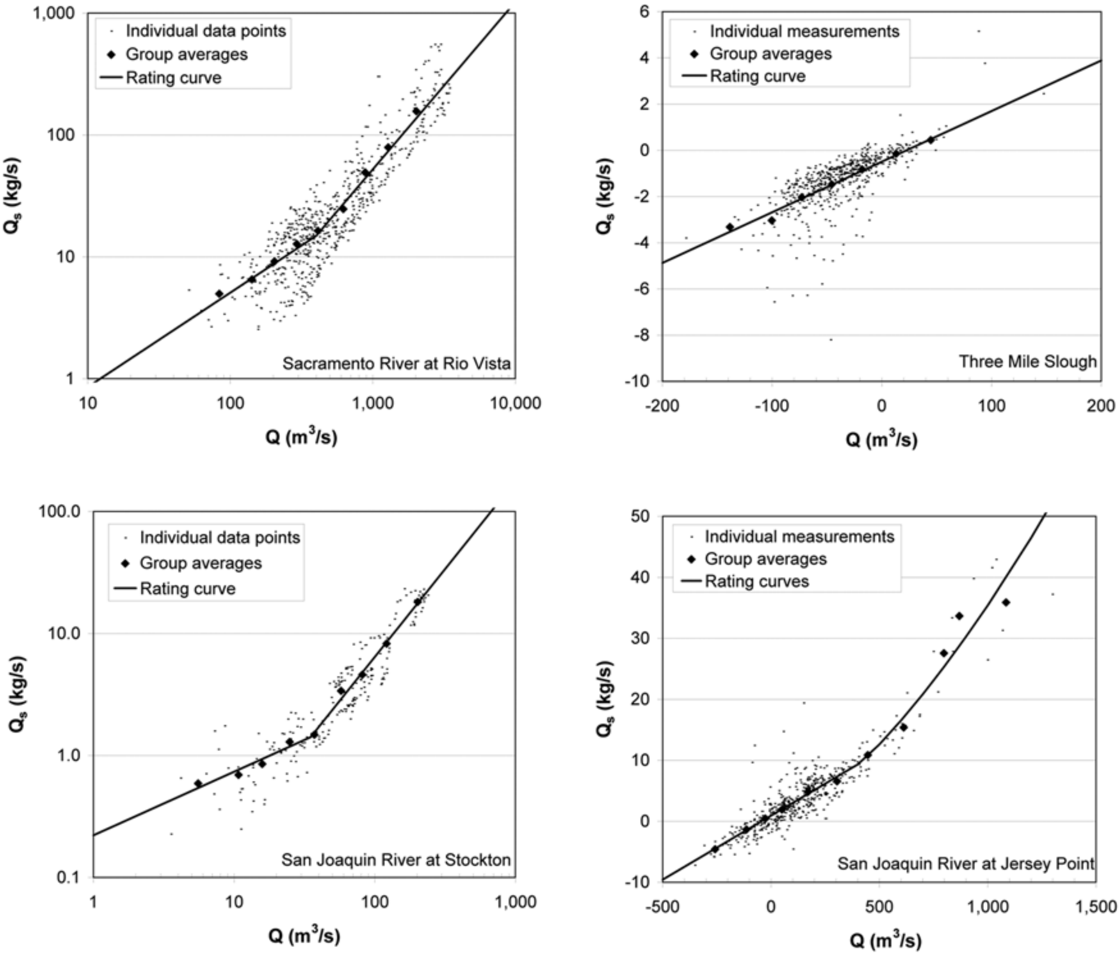

Figure 7. Daily suspended-sediment rating curves for four of the optical sensors sites.

DAYFLOW program description, http://www.iep.water.ca.gov/dayflow/index.html). DAYFLOW is a daily water routing model for the delta and comparisons between DAYFLOW and the measured flows at Rio Vista and Jersey point showed good agreement. The missing flow data for the San Joaquin River at Stockton (~14%) were estimated using a correlation with the daily flows at Vernalis (~46 km upstream). No satisfactory method was available for estimating missing flow data for Three Mile Slough (TMS). Therefore annual flow and transport estimates are unavailable for water years 1999 and 2000 for TMS.

[24] The daily OBS-derived suspended-sediment records for RVS, STN, JPT, and TMS contained significant gaps due to biological fouling as detailed in Table 1 (gaps of less than one hour were filled with linear interpolation before daily averaging). In order to develop annual sediment budgets, these gaps in the records were filled using rating curves between daily flow and daily suspended-sediment flux. The group averaging technique was used to develop the rating curves [*Glysson*, 1987], the results of which are shown in Figure 7 and Table 3. Table 3 also includes the percentage of days with fouled data and the percentage of total transport over the entire time period that was estimated using the rating curve. The fact that the percentage of the flux estimated with the rating curve is less than the percentage of days with fouled data indicates that the biological fouling was typically the worst in the summer when fluxes were lowest.

[25] The measurement error of the OBS-derived suspended-sediment flux was estimated by considering four sources of error: relation of OBS to $SSC_{xs,}$ laboratory error of SSC_{xs}, error of measured and actual SSC_{xs}, and error of the flow estimate. The error in the relation of OBS to SSC_{xs} was taken as the concentration-weighted mean absolute error of the OBS calibrations for each site (Figure 4). The error was weighted by concentration because sediment flux increases with concentration and error at relatively low concentrations will have little effect on the flux while error at high concentrations is most important. Laboratory error in SSC for water samples analyzed by filtration varies with SSC [*ASTM International*, 2000]. Mean SSC from each station was used to calculate the error in Table 4. SSC_{xs} was measured by averaging 5 depth-integrated samples collected at equal cumulative discharge increments in the cross section. A conservative estimate of the error is the SSC_{xs}-weighted percent deviation of each depth-integrated sample from the corresponding SSC_{xs}. This assumes that the mean deviation of the five depth-integrated samples from the corresponding SSC_{xs} is equal to the deviation (or error) of the mean of the 5 depth integrated samples from the actual SSC_{xs}. *Simpson and Bland* [2000] calculated that the error of instantaneous flow at TMS was 1.4%. This error was assumed to apply to each site and the errors were combined

Table 3. Daily Suspended-Sediment Rating Curves for OBS Sites[a]

Site	Rating Curve	Percent Days With Fouled Data	Percent of Total Flux Estimated With Rating Curve
Sacramento River at Rio Vista	$Q_s = 0.14Q^{0.77}$ $Q \leq 400$	59	30
	$Q_s = 0.0041Q^{1.37}$ $Q > 400$		
Three Mile Slough	$Q_s = 0.022Q - 0.49$	69	53
San Joaquin River at Stockton	$Q_s = 0.22Q^{0.52}$ $Q \leq 35$	88	82
	$Q_s = 0.0085Q^{1.44}$ $Q > 35$		
San Joaquin River at Jersey Point	$Q_s = 0.21Q + 0.93$ $Q \leq 400$	71	68
	$Q_s = 0.0012Q^{1.49}$ $Q > 400$		

[a]Q_s in kg/s; Q in m^3/s.

with quadrature, a standard technique for propagating random measurement errors.

[26] The total error of measured suspended-sediment flux varies from 25 to 39% (Table 4). The greatest source of error is in the calibration of the point OBS to SSC_{xs}. During high flow, turbid waters from the Sacramento River and Yolo Bypass join 3 km upstream from Rio Vista and do not laterally mix at Rio Vista. Thus Rio Vista has the greatest error. These errors are for the individual measurements of sediment flux, whereas we are interested in applying error estimates to the annual sediment budget. When summing to get the annual fluxes, random errors would tend to cancel out while systematic errors would propagate directly to the summations. Since it is unknown what proportion of the error is random versus systematic, it was conservatively assumed that the individual measurement errors apply directly to the annual flux estimates. Also, when adding and subtracting the annual fluxes for the sediment budgets, the errors were propagated to the result using quadrature (i.e., it was assumed that the errors are Gaussian).

[27] The daily flow past Mallard Island just downstream from the Sacramento-San Joaquin confluence was taken from DAYFLOW records. The daily suspended-sediment flux at this site has been estimated by *McKee et al.* [2002] based on optical backscatter records and point concentration measurements.

[28] The Yolo Bypass diverts water from the Sacramento River at two locations: Fremont Weir upstream from Sacramento and the Sacramento Weir. The diverted water reenters the Sacramento River just upstream from Rio Vista via Cache Slough. Daily flows were taken from DAYFLOW which computes the total flow as the sum of three sources: (1) flow in the bypass near Woodland (USGS gage 11453000) which accounts for the spill over Fremont Weir, (2) the Sacramento Weir spill (USGS gage 11426000), and (3) the South Fork of Putah Creek. An estimate of daily suspended-sediment flux in the Yolo Bypass was made using a rating curve based on data from the gage near Woodland. Forty-five sediment flux measurements were made between 1957 and 1961 with an additional three measurements in 1980. The rating curve is shown in Figure 8, and the equation is given in Table 5. The error (±43%) was estimated as the sediment discharge-weighted mean absolute error from the rating curve. This rating curve represents sediment flux resulting from Fremont Weir spill only and does not account for Sacramento Weir spill or South Putah Creek flows. However, during the period of interest here, water years 1999–2002, the Sacramento Weir did not spill. Also, sediment fluxes on South Putah Creek are expected to be small due to a large impoundment just upstream from the Bypass (Lake Berryessa). Therefore it is expected that the fluxes resulting from the rating curve represent a high percentage of the total Yolo Bypass flux for 1999–2002, if it is assumed that the rating curve based on the historic data is valid for this period. Discharge at the Woodland gage from 1999–2002 ranged from 29 to 1781 m^3/s, well within the range of discharges used for the rating curve (maximum of 3510 m^3/s).

[29] The primary sources of sediment to the delta from east side tributaries are the Cosumnes and Mokelumne rivers. Flows for the east side tributaries (EAST in Figures 1 and 5) were taken from DAYFLOW and include flows from the Cosumnes and Mokelumne as well as the Calaveras River and French Camp Slough. Daily suspended-sediment flux records for the Cosumnes and Mokelumne were developed using rating curves. The Cosumnes River rating curve is based on data from USGS gage 11335000 (near Michigan Bar) which include 80 flux measurements between 1965 and 1974 and 13 measurements during water year 2002. The Mokelumne River rating curve is based on data from USGS gage 11325500 (at Woodbridge) which include 125 flux measurements between 1974 and 1994. The rating curves are presented in Figure 8 and the equations are given in Table 5. The combined error from the two rating curves (sediment discharge-weighted mean absolute error) is ±22%.

[30] Daily flows for the Delta Cross Channel and Geogiana Slough (DCC in Figures 1 and 5) were taken from DAYFLOW. Unfortunately no sediment data is available to quantify the sediment flux through these channels.

Table 4. Errors of Measured Suspended-Sediment Flux at OBS Sites

	Error, %			
	Rio Vista	Three Mile Slough	Jersey Point	Stockton
OBS surrogate for SSC_{xs}	34.6	20.6	19.8	28.8
Laboratory measurement of SSC	7.0	10.6	11.0	6.5
Measured and actual SSC_{xs}	17.0	10.5	12.1	21.1
Flow	1.4	1.4	1.4	1.4
Total	39	25	26	36

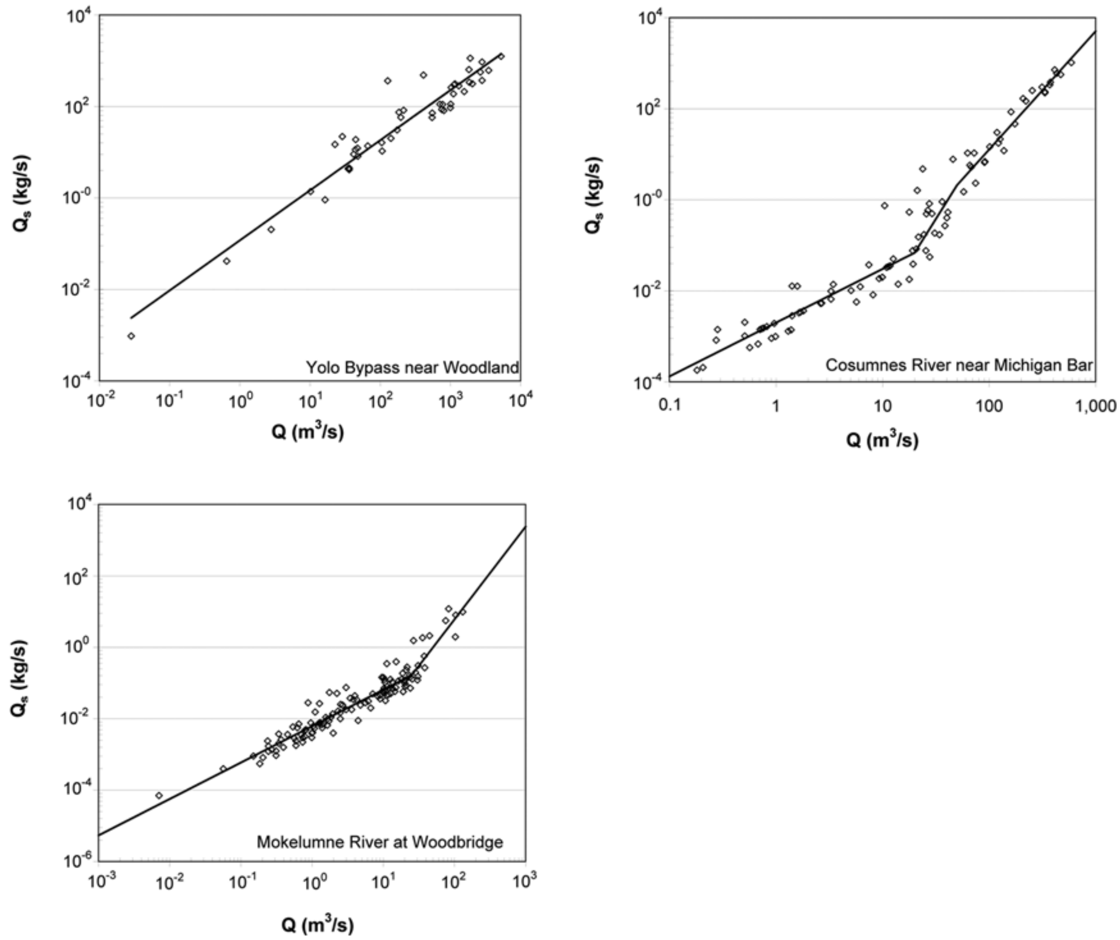

Figure 8. Suspended-sediment rating curves for the Yolo Bypass near Woodland, Cosumnes River near Michigan Bar, and Mokelumne River at Woodbridge.

[31] Both the San Joaquin River and smaller Dutch Slough provide pathways from the South Delta to San Francisco Bay. Flow in Dutch Slough was measured in water years 1999–2002 [*Ruhl and Simpson*, 2005]. Suspended sediment time series in water year 2000 did not produce reliable results. SSC_{xs} was relatively small (mean of 12 samples was 13 mg/L) compared to the San Joaquin River at Jersey Point (22 mg/L for 44 samples). Net flow in Dutch Slough (0.02 billion m^3/year) was two orders of magnitude smaller than at Jersey Point (4.1 billion m^3/year). Thus we assume that the suspended sediment flux in Dutch Slough was negligible compared to that in the San Joaquin River.

[32] Daily water exports to the State Water Project and Central Valley Project (EXP in Figures 1 and 5) were also taken from DAYFLOW. Water to be exported resides in Clifton Court Forebay before being pumped. For sediment budgeting purposes it is assumed that all sediment in the export water deposits in the Forebay. From 1999 to 2004, 116,000 m^3 of sediment deposited in the Forebay (S. Woodland, California Department of Water Resources, personal communication, 2005). Assuming a bed sediment density of 850 kg/m^3 [*Porterfield*, 1980], the annual rate of deposition was about 20,000 t per year.

4.2. Annual Sediment Budget

[33] The continuous daily flow and sediment records developed as described in the previous section were used to compute the annual water and suspended-sediment budgets for the delta. Figure 9 presents the results in terms of

Table 5. Daily Suspended-Sediment Rating Curves for Yolo Bypass, Cosumnes River, and Mokelumne River[a]

Site	Data Points	Date Range	Rating Curve	
Yolo Bypass near Woodland	48	1957–1961, 1980	$Q_s = 0.12Q^{1.09}$	
Cosumnes River near Michigan Bar	93	1965–1974, 2002	$Q_s = 0.002Q^{1.18}$	$Q \le 20$
			$Q_s = 9.7 \times 10^{-7}\ Q^{3.73}$	$20 < Q \le 50$
			$Q_s = 8.0 \times 10^{-5}\ Q^{2.6}$	$Q > 50$
Mokelumne River at Woodbridge	125	1974–1994	$Q_s = 0.0062Q^{1.05}$	$Q \le 25$
			$Q_s = 3.8 \times 10^{-5}\ Q^{2.6}$	$Q > 25$

[a]Q_s in kg/s; Q in m^3/s.

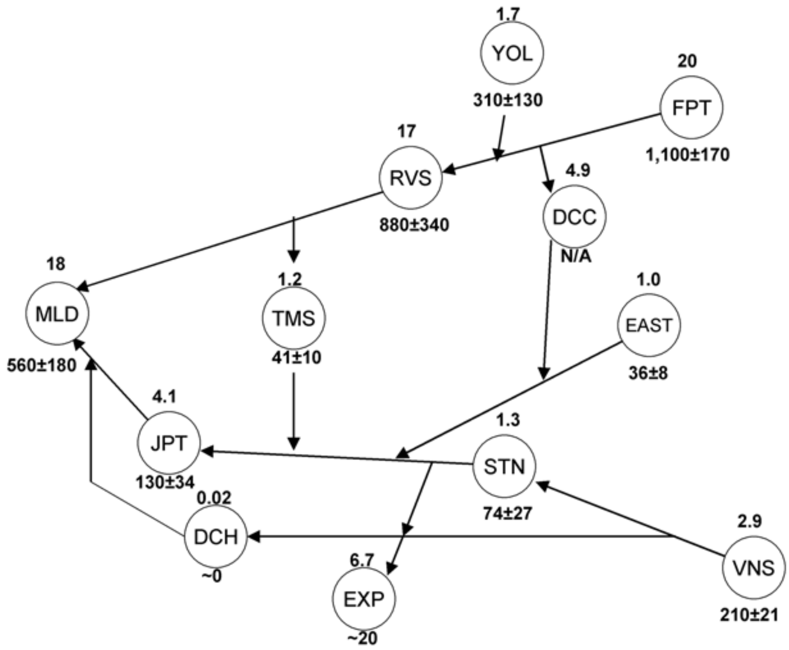

Figure 9. Average annual delta water and sediment budgets based on water years 1999–2002, except for TMS, which is based on water years 2001 and 2002 only. For each location the top number is annual water flux in billion m^3, and the bottom number is annual suspended-sediment flux and the estimated error in thousand metric tons.

annual averages over the period 1999–2002, except for Three Mile Slough, which is based on water years 2001 and 2002 only.

[34] The Sacramento River dominates sediment inflows to the delta. The combined sediment inflow from the Sacramento River at Freeport and the Yolo Bypass (which is water and sediment diverted from the Sacramento) accounts for 85% of the total inflow over the 4 year period. The San Joaquin River accounts for about 13% and the east side tributaries (Cosumnes and Mokelumne rivers) account for the remaining 2%.

[35] Over the 4 year period the ratio of total sediment outflow to total sediment inflow was 0.33, indicating that 67 ± 17% of the sediment that entered the delta during this time period was deposited (4.4 ± 1.1 Mt). The amount of sediment deposited ranges from a maximum of 73% in 2000 and 2002 to a minimum of 57% in 1999. For 1999–2002, 42 ± 24% of the input sediment was deposited landward of Rio Vista, Three Mile Slough, Jersey Point, and Dutch Slough and 25 ± 23% was deposited seaward. Despite the greater error caused by the relatively large error at Rio Vista, the data indicates that deposition occurred in both the landward and seaward sides of the delta.

[36] *Reed* [2002] measured sediment accumulation at several natural and restored wetland sites in the delta. Five measurements of inorganic sediment accumulation on natural wetlands from March 1998 to August 2000 had a mean value of 3.6 g/cm^2/yr and a standard deviation of 1.8 g/cm^2/yr (Figure 1). To convert our depositional mass to a depositional rate on wetlands, areas with permanently flooded, seasonally flooded, and tidal estuarine and palustrine emergent vegetation were assumed to be the only depositional areas in the delta [*California Department of Fish and Game*, 1997]. This assumption is appropriate because there are very few nonvegetated tidal flats in the delta due to levees and channelization. According to this definition there is approximately 75 km^2 of area available for deposition. In water years 1999 and 2000 (October 1998 to September 2000), we estimate that an average of 2.0 g/cm^2/yr of inorganic sediment deposited on vegetated wetlands in the delta. Given the large spatial variation in deposition rates observed by *Reed* [2002] and that our estimate excludes high flows and sediment load during spring 1998, the estimated deposition rate compares favorably with measurements.

[37] Despite a 50% decrease in sediment supply from the Sacramento River from 1957 to 2001 [*Wright and Schoellhamer*, 2004] the delta remains depositional. Reduced supply of erodible sediment in the watershed following cessation of hydraulic mining in the late 19th century and sediment trapping behind reservoirs are primarily responsible for the decreased supply. The decrease in sediment supply during the 20th century caused northern San Francisco Bay to become erosional [*Cappiella et al.*, 1999; *Jaffe et al.*, 1998] while the delta remains depositional. We hypothesize that this difference is caused by (1) a larger fraction of depositional area in the delta where at least one third of the tidally influenced surface area is wetlands, breached islands, or dead-end sloughs compared to 21% wetlands in northern San Francisco Bay [*San Francisco Bay Area Wetlands Ecosystem Goals Project*, 1999] and (2) the first depositional opportunity for sediment transported down the Sacramento River is in the delta where slack tides and large depositional areas are encountered before sediment can enter the Bay. Thus deposition in the delta is likely to occur independent of the magnitude of sediment supply, although the deposition rate would decrease as supply decreases.

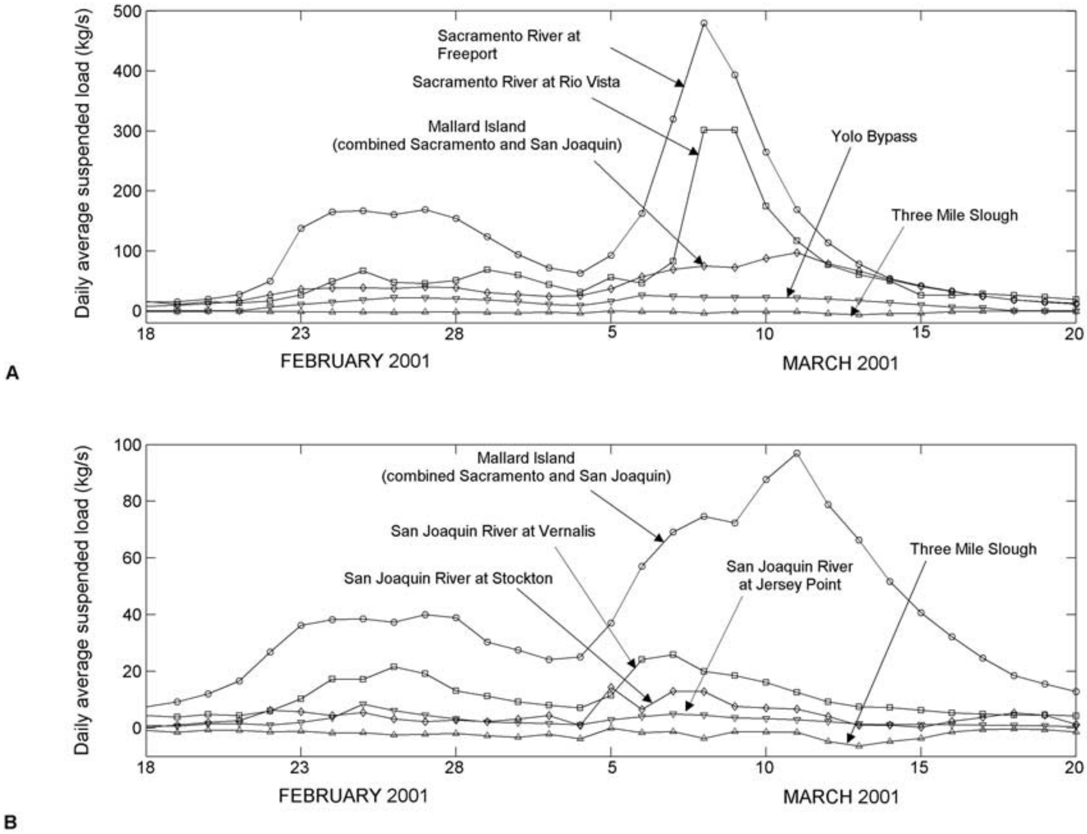

Figure 10. Movement of the main sediment pulse of water year 2001 down the (a) Sacramento and (b) San Joaquin rivers. Three Mile Slough flux is positive from the San Joaquin River to the Sacramento River.

[38] This sediment budget is for a 4 year period for which the average water inflow was 19% less than the historical average and for which there was significant interannual variability. The average annual delta inflow during the 4 year study period (water years 1999–2002) was 25 billion m^3/yr and from 1956 to 2002 it was 31 billion m^3/yr (see DAYFLOW program description). For water years 1999–2002 the annual suspended-sediment fluxes of the Sacramento River and Yolo Bypass were 1.8, 2.1, 0.59, and 1.1 Mt, respectively. The mean value was 1.4 Mt.

[39] The budget presented here is for the transitional zone where rivers become an estuary so these results, especially the percentage of sediment deposition, are not directly comparable to other estuarine budgets which consider an entire estuary and extend to the continental shelf. The continental shelf can be a major source of sediment to some estuaries [*Hobbs et al.*, 1992; *Eyre et al.*, 1998] but this is not the case in this study because the seaward boundary of the delta is 75 km landward from the continental shelf. Shoreline erosion is another major source of sediment in some estuaries [*Schubel and Carter*, 1976; *Yarbro et al.*, 1983] that is probably minor in the delta because levees with rip rap bound most of the channels.

4.3. Wet Versus Dry Periods

[40] Wet and dry periods were analyzed separately to determine if the overall trend of deposition was common through both or if periods of erosion were apparent. For each year, the wet period was determined by visually examining the flow records for all of the inflows. The following wet periods were determined: water year 1999, 28 November 1998 to 20 May 1999; water year 2000, 15 January 2000 to 24 May 2000; water year 2001, 4 January 2001 to 30 March 2001; water year 2002, 20 November 2001 to 24 January 2002. The wet periods constituted 464 days of the 4 year record, or 31% of the total time, but as expected, the majority of sediment was delivered during these wet periods (82%). Deposition occurred during both wet and dry periods for all water years, though wet periods tended to be slightly more depositional, in terms of the ratio of outflow to inflow. During wet periods approximately 69% of sediment inflow was deposited, while for dry periods only 56% of incoming sediment was deposited. Thus 85% of deposition occurred during the wet season. Episodic delivery of sediment from rivers to an estuary is common [*Schubel and Carter*, 1976; *Hossain and Eyre*, 2002] and, in this study, slightly more episodic deposition resulted.

5. Sediment Transport Pathways

[41] Two pathways exist that connect the north delta (Sacramento River) to the south delta (San Joaquin River): the Delta Cross Channel/Georgiana Slough and Three Mile Slough. Annual fluxes for 2001 and 2002 for Three Mile Slough were 49 and 33 kt, respectively, from north to south.

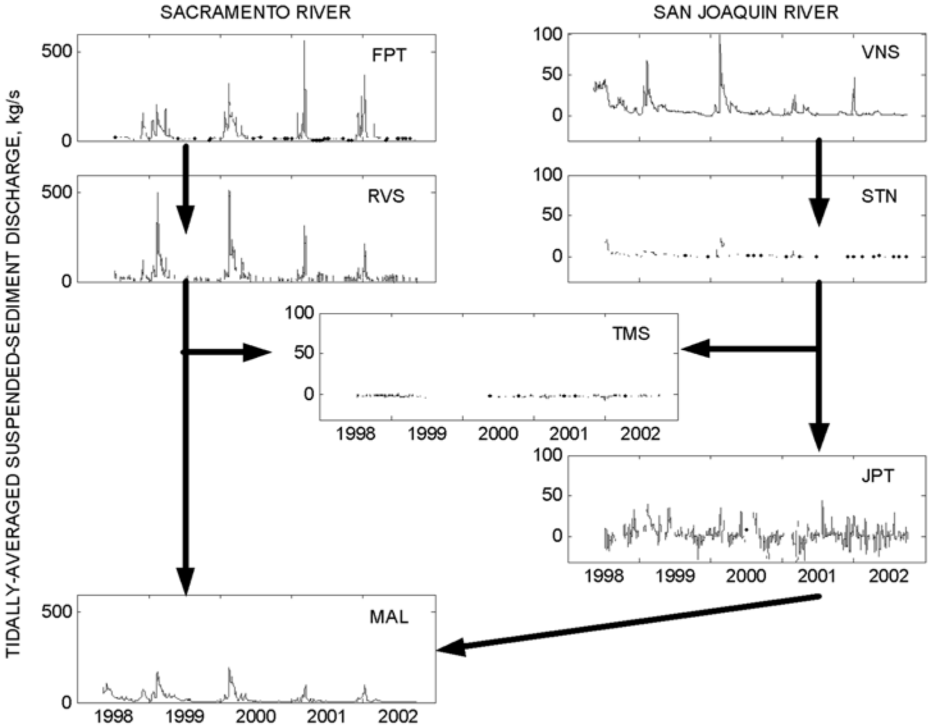

Figure 11. Tidally averaged suspended sediment flux. Arrows indicate downstream/down estuary flow paths for the (left) Sacramento and (right) San Joaquin rivers. The vertical scale for the Sacramento River flow path is larger than that for the San Joaquin River flow path and Three Mile Slough (TMS).

These fluxes are only 10% and 5% of the transport past Rio Vista, respectively, suggesting that a large majority of sediment moving past Rio Vista either deposits in the Sacramento River or moves past Mallard Island. Unfortunately, sediment transport at the Delta Cross Channel was not monitored. If it is assumed that no deposition occurred between Freeport and DCC, then SSC at DCC would equal that at Freeport. This assumption leads to an estimation of the upper bound of sediment flux at DCC equal to 20% of the flux past Freeport. Thus at least 82% of the sediment entering the delta from the Sacramento River watershed (Freeport and Yolo Bypass) either deposits along the Sacramento River or moves past Mallard Island and into San Francisco Bay. No more than 18% of Sacramento River sediment moves toward the San Joaquin River. Figure 10 illustrates the movement of a sediment pulse down the Sacramento River (main pulse of water year 2001); note the decreasing flux in the downstream direction and the absence of the pulse in Three Mile Slough.

[42] Figure 10 also shows the movement of the sediment pulse down the San Joaquin River for the same time period. Again, the difference in the magnitude of transport between the San Joaquin and Sacramento is apparent. The river pulse is also seen to diminish in the downstream direction from Vernalis to Stockton to Jersey Point. The annual fluxes indicate a significant loss of sediment in the reach of the San Joaquin between Vernalis and Stockton. For water years 1999–2002, the ratios of transport past Stockton to that past Vernalis were 0.38, 0.41, 0.28, 0.30, respectively. The sediment is either depositing within this reach, or entering the south delta complex through Middle River. Downstream from Stockton the situation becomes complicated, with the addition of the eastside tributaries and the unknown flux of sediment through the Delta Cross Channel and Georgiana Slough. Also, State Water Project and Central Valley Project pumping removes water from the south delta but it is unknown exactly where the water comes from. More monitoring would be required quantify the sediment budgets of individual reaches within the south delta complex.

5.1. Riverine Signal Attenuation

[43] As one moves from a river into an estuary, the relative strength of the riverine signal (or discharge) will diminish as the tidal signal (or fluctuations) strengthens. In order to quantify the attenuation of the riverine signals along the Sacramento and San Joaquin River flow paths, singular spectrum analysis for time series of missing data (SSAM) was used to tidally average the 15 min suspended-sediment flux time series. *Schoellhamer* [2001] describes SSAM in detail. In this study, SSAM provides a tidally averaged time series containing periodicities greater than 40 hours. This time series is assumed to be the riverine signal at each site. The percent of the total variance of suspended-sediment flux contained in the tidally averaged time series is also calculated. Tidal and meteorological forcing that would cause suspended-sediment flux to vary at periodicities greater than 40 hours are assumed to be minor.

[44] Along the Sacramento River flow path, the riverine signal is large and discernable at Rio Vista and Mallard Island (Figure 11). The riverine signal at Rio Vista contains 35.1% of the total variance and is well correlated with the Freeport riverine signal when lagged 1.5 days (Table 6). Tidally averaged suspended-sediment flux is greater at Rio

Table 6. Results of SSAM Analysis of Suspended-Sediment Flux Along the Sacramento River[a]

	Percent of Total Variance in SSAM Tidally Averaged Suspended-Sediment Flux Time Series	Lagged Correlation Coefficient r With Freeport	Lag From Freeport, days
Sacramento River at Freeport	97.0	1.00	0.0
Sacramento River at Rio Vista	35.1	0.71	1.5
Three Mile Slough	0.5	−0.61	2.5
Mallard Island	-	0.68	3.0

[a]Flow in Three Mile Slough is positive from the San Joaquin River to the Sacramento River, so r is negative. All correlations are significant at the less than 0.001 level.

Vista than Freeport when the Yolo Bypass is flowing during the highest water discharges in 1999 and 2000. Further downstream at Three Mile Slough (off the main Sacramento flow path), the riverine signal is only 0.5 percent of the total variance and is well correlated with the Freeport riverine signal when lagged 2.5 days (Table 6). Comparison of daily suspended-sediment flux at Mallard Island with daily values from Freeport shows a good correlation for a lag of 3.0 days. Thus the lag in the riverine signal increases with downstream distance as expected. The riverine signal in Three Mile Slough is very small, confirming that most Sacramento River suspended-sediment that passes Rio Vista remains in the river.

[45] Along the San Joaquin River flow path, the riverine signal is smaller and less discernable than for the Sacramento River (Figure 11). Flow direction slightly reverses at Stockton whereas at Freeport flow is unidirectional, so the riverine signal at Stockton is weaker than at Freeport (Table 7). Daily suspended-sediment flux is well correlated between Stockton and Vernalis ($r = 0.93$ for no lag, $p < 0.001$). The riverine signal at Three Mile Slough is not as well correlated with the San Joaquin River (Table 7) as it is with the Sacramento River. The riverine signal is only 1.4% at Jersey Point and is poorly correlated with the Stockton riverine signal for a physically unrealistic zero lag. Comparison of daily suspended-sediment flux at Mallard Island with daily values from Vernalis shows a good correlation for a lag of 2.0 days. Suspended-sediment flux at Freeport and Vernalis covary ($r = 0.65$ for no lag, $p < 0.001$), which probably explains the good correlation between Mallard Island and Vernalis. Compared to the Sacramento River flow path, suspended-sediment flux along the San Joaquin River flow path is smaller and the riverine signal attenuates more rapidly.

5.2. Implications for Wetland Restoration

[46] The sediment supply available for deposition on wetland restoration sites is a crucial constraint on wetland restoration projects [*Krone and Hu*, 2001; *Williams and Orr*, 2002]. The main pathway for sediment transport from the watershed to the Bay is along the Sacramento River channel. Suspended-sediment concentration and flux and the riverine signal are greatest along this path. In the San Joaquin River and Three Mile Slough, which connects the two major rivers, sediment concentration and flux are much smaller, and the riverine signal is minor compared to the tidal signal. Thus sediment supply is greatest along the Sacramento River channel. This is also demonstrated by inorganic sediment accumulation rates in the delta which are greatest at sites close to inputs from the Sacramento River [*Reed*, 2002]. If all other factors are equal, wetland restoration projects directly connected to the Sacramento River will have the greatest sediment supply and greatest probability of success relative to elsewhere in the delta.

[47] The greatest sediment supply and deposition rates occur during the wet season. 82% of the sediment supply and 85% of the deposition occurred during the wet seasons, which were 31% of our study period. Wetland restoration projects, especially those for which initial rapid deposition is desired, should be timed accordingly.

6. Conclusions

[48] In this paper, we have presented the detailed methods of data collection and analyses in order to quantify the suspended-sediment budget of the Sacramento–San Joaquin River Delta, a large, complex system where several rivers meet to form an estuary (San Francisco Bay). The primary regional goal of the study was to measure sediment transport rates and pathways in the delta in support of ecosystem restoration efforts. In addition to achieving this regional goal, the study has produced general methods to collect, edit, and analyze (including error analysis) sediment transport data at the interface of rivers and estuaries. Estimating sediment budgets for these systems is difficult due to the mixed nature of riverine versus tidal transport processes, the different timescales of transport in fluvial and tidal environments, as well as the sheer complexity and size of

Table 7. Results of SSAM Analysis of Suspended-Sediment Flux Along the San Joaquin River[a]

	Percent of Total Variance in SSAM Tidally Averaged Suspended-Sediment Flux Time Series	Lagged Correlation Coefficient r With Stockton	Lag From Stockton, days
San Joaquin River at Stockton	69.2	1.00	0.0
Three Mile Slough	0.5	0.16	2.6
San Joaquin River at Jersey Point	1.4	0.08	0.0
Mallard Island	-	0.83	2.0

[a]All correlations are significant at the less than 0.001 level.

systems such as the Sacramento–San Joaquin River Delta. Sediment budgets also require error estimates in order to assess whether differences in inflows and outflows, which could be small compared to overall fluxes, are indeed distinguishable from zero. The main findings related to methods and analyses which may be of interest to sediment transport researchers studying other river/estuary systems are as follows.

[49] 1. Optical backscatter sensors installed near the bank were found to correlate well with cross-sectionally integrated suspended-sediment samples for the conditions encountered in this study. For the riverine site on the Sacramento River (Freeport), comparisons of the loads using OBS with daily loads using standard USGS protocols were favorable. This indicates that OBS can be a useful technique for estimating suspended-sediment transport in both rivers and estuaries under certain conditions, such as when particle size and color, parameters known to significantly affect the relationship between backscatter and concentration [*Sutherland et al.*, 2000], are relatively constant.

[50] 2. Biological fouling was common on the OBS sensors, typically leading to editing out of around 50% of the data. This could be minimized by frequent cleaning but this can be logistically difficult. For the sites in this study we were able to fill in these gaps using relationships between daily flow and daily sediment transport developed from periods when the OBS sensors were clean. Since compiling the results presented here, we have installed sensors equipped with wipers that have significantly reduced biological fouling and resisted corrosion in brackish waters when continuously deployed at these sites.

[51] 3. Over the 4 year study period, we found that the relationship between OBS and SSC exhibited consistent drift in time that could not be correlated with any physical parameter (such as particle size, temperature, or salinity). Though the exact reason for the drift is unknown, we speculate that it is a result of wear and tear on the sensors.

[52] 4. An error analysis is presented which accounts for the sources of error from the various components used to compute the suspended-sediment flux, including (1) the relationship between OBS and sediment concentration, (2) laboratory determinations of sediment concentration, (3) field measurements of sediment concentration, and (4) flow measurements. These errors are combined to provide an overall estimate of the uncertainty associated with a given suspended-sediment flux measurement.

[53] 5. A method is presented for decomposing suspended-sediment flux records into riverine and tidal signals in order to track the relative importance of a riverine sediment pulse as it moves through an estuary.

[54] 6. The deposition rate computed from the sediment transport measurements compares favorably with five nearly concurrent measurements of inorganic sediment accumulation on natural vegetated wetlands in the delta, providing confidence in the methodologies described in this paper for quantifying sediment budgets in regions of combined riverine and tidal influence.

[55] The detailed results of the sediment budget for the Sacramento–San Joaquin River Delta are of interest to resource managers in the San Francisco Bay area, as well as for comparison purposes for researchers studying other river/estuary transitions. The primary findings related specifically to the delta sediment budget are summarized as follows.

[56] 1. Over the 4 year period, 6.6 ± 0.9 Mt of suspended-sediment entered the delta. Of this total, 85% came from the Sacramento River (including the Yolo Bypass), 13% came from the San Joaquin River, and 2% was from eastside tributaries. Unlike many other estuaries, the continental shelf (75 km down estuary from the delta) and erosion of the well-armored shorelines of the delta channels were not significant sediment sources. Over the same period, 2.2 ± 0.7 Mt (67 ± 17%) of suspended-sediment exited the delta past Mallard Island, leaving a deficit of 4.4 ± 1.1 Mt for deposition within the delta. This result is for the transitional zone where rivers become an estuary and is not directly comparable to other estuarine sediment budgets which consider an entire estuary and extend to the continental shelf.

[57] 2. The Sacramento River is the primary pathway for sediment transport. At least 82% of the sediment entering the delta from the Sacramento River watershed either deposits along the Sacramento River or moves past Mallard Island and into San Francisco Bay. No more than 18% of Sacramento River sediment moves through the complex network of channels toward the San Joaquin River. Sediment flux in Three Mile Slough, a primary pathway between the Sacramento and San Joaquin rivers, is only 5–10% of the flux in the Sacramento River. As a pulse of sediment moves down the Sacramento River, almost no impact is seen on the flux through Three Mile Slough. Further, the riverine signal at Three Mile Slough is only 0.5% of the total variance of flux.

[58] 3. Similar to other estuaries, riverine sediment delivery to the delta was episodic with 82% of the sediment being delivered during the wet period (31% of the time). Sediment deposited during both wet and dry periods, though wet periods were slightly more depositional. Thus episodic sediment delivery results in slightly enhanced episodic sediment deposition in the delta.

[59] 4. On the San Joaquin River, significant loss of sediment occurs over the reach between Vernalis and Stockton (64% over the 4 year period). This sediment is either deposited in the reach or enters the south delta channel complex through Middle River.

[60] 5. Tidally averaged suspended-sediment flux at the delta sites indicates that the suspended-sediment signal of the San Joaquin River attenuates more rapidly than that of the Sacramento River.

[61] 6. Because the Sacramento River is the primary pathway for sediment transport, wetland restoration projects directly connected to the Sacramento River will have the greatest sediment supply and greatest probability of success relative to elsewhere in the delta, assuming that all other factors are equal. 85% of the deposition in the delta occurs during the wet season and wetland restoration projects should be planned accordingly.

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