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Trends in the Sediment Yield of the Sacramento River, California, 1957 – 2001

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ABSTRACT

Human activities within a watershed, such as agriculture, urbanization, and dam building, may affect the sediment yield from the watershed. Because the equilibrium geomorphic form of an estuary is dependent in part on the sediment supply from the watershed, anthropogenic activities within the watershed have the potential to affect estuary geomorphology. The Sacramento River drains the northern half of California's Central Valley and is the primary source of sediment to San Francisco Bay. In this paper, it is shown that the delivery of suspended-sediment from the Sacramento River to San Francisco Bay has decreased by about one-half during the period 1957 to 2001. Many factors may be contributing to the trend in sediment yield, including the depletion of erodible sediment from hydraulic mining in the late 1800s, trapping of sediment in reservoirs, riverbank protection, altered land-uses (such as agriculture, grazing, urbanization, and logging), and levees. This finding has implications for planned tidal wetland restoration activities around San Francisco Bay, where an adequate sediment supply will be needed to build subsided areas to elevations typical of tidal wetlands as well as to keep pace with projected sea-level rise. In a broader context, the study underscores the need to address anthropogenic impacts on watershed sediment yield when considering actions such as restoration within downstream depositional areas.

KEYWORDS

Sediment yield, Sacramento River, suspended-sediment transport, hydraulic mining, reservoir sedimentation, land-use impacts, watershed disturbance.

SUGGESTED CITATION

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INTRODUCTION

River systems transport sediment from erosional areas of watersheds to depositional areas, such as lowland floodplains and estuaries. Over long-term geomorphic time scales, the processes of erosion and deposition, along with sea-level change, likely attain some form of geomorphic equilibrium that includes the landforms found in estuaries, such as tidal wetlands. Humans have the potential to disrupt this balance by altering the processes on either end of the system. Changes in land-use activities within the watershed, such as urbanization, agriculture, and dam building, have the potential to alter the sediment yield from erosional areas. At the downstream end, diking and filling of depositional areas such as wetlands may lead to redistribution of sediment and deposition in previously open water environments. For example, sedimentation rates in Chesapeake Bay have increased two- to three-fold since European settlement (Donoghue 1990; Zimmerman and Canuel 2002). In addition, changes in the delivery of sediment from the watershed may affect turbidity in the estuary, and thus photosynthesis and primary production (Cloern 1987), as well as the delivery, distribution, and fate of sediment related contaminants (Domagalski and Kuivila 1993; Flegal and others 1996; Schoellhamer and others 2003). The Central Valley of California, USA, and San Francisco Bay (Figure 1) have experienced significant human influences since the discovery of gold in Sierra Nevada foothills in 1849. In this paper, the effects of human development on the sediment yield of the Sacramento River are studied by examining suspended-sediment records for 1957 through 2001.

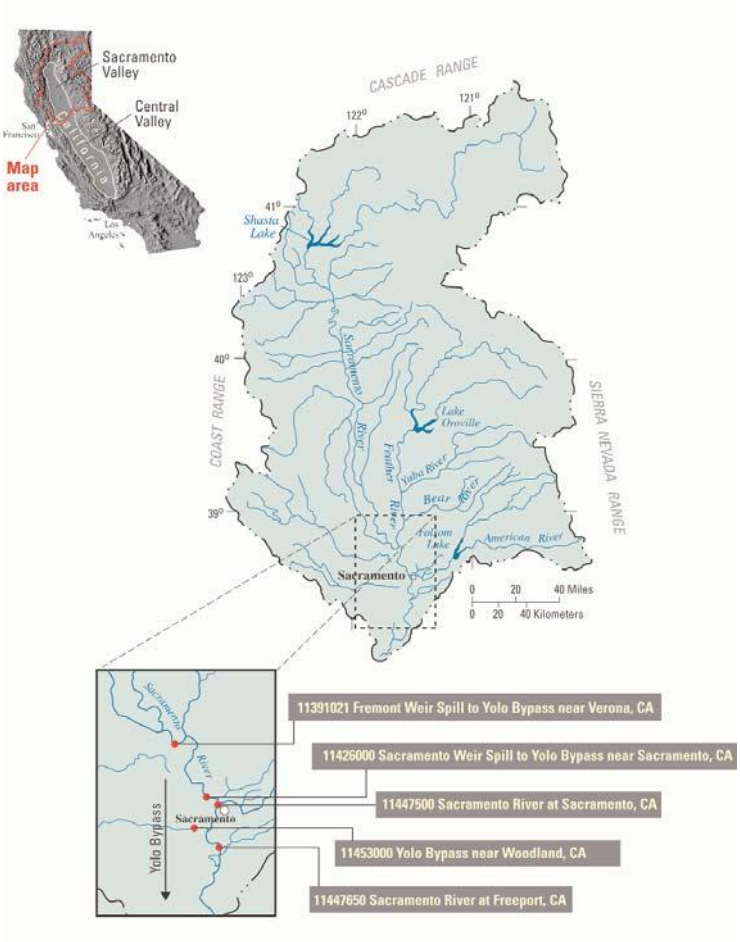

Figure 1. Site map of the Sacramento River watershed, California. 8-digit numbers denote USGS gage stations.

The Sacramento River drains approximately 68 million km² of the northern half of California's Central Valley (Figure 1). The watershed is bounded on the west by the Coast Range, on the north by the Cascades, and on the east by the Sierra Nevada. The mountain ranges and foothills supply sediment to the major river systems, which drain to San Francisco Bay (Bryan 1923; Harwood and Helley 1987). The Sacramento River drains the northern portion of the Central Valley and delivers the majority of sediment to San Francisco Bay, approximately seven times the sediment yield of the San Joaquin River (Oltmann and others 1999), which drains the southern portion of the valley. Several previous studies have estimated the annual sediment yield of Central Valley rivers and/or sediment delivery to and through San Francisco Bay. Gilbert (1917) estimated the pre-hydraulic mining and peak mining sediment yield to be approximately 0.8 and 7.3 million metric tons per year, respectively, illustrating the dramatic effect of gold-related hydraulic mining in the watershed (discussed further in the "Discussion" section, page 9). More recent estimates (Krone 1979, 1996; Porterfield 1980; Ogden Beeman 1992; McKee and others 2002) are less than that of the mining peak and indicate that sediment yield decreased during the 20th century (Figure 2). In addition to hydraulic mining the following anthropogenic activities are among those affecting erosion, transport, and deposition dynamics within the watershed: altered land-use (agriculture and urbanization),

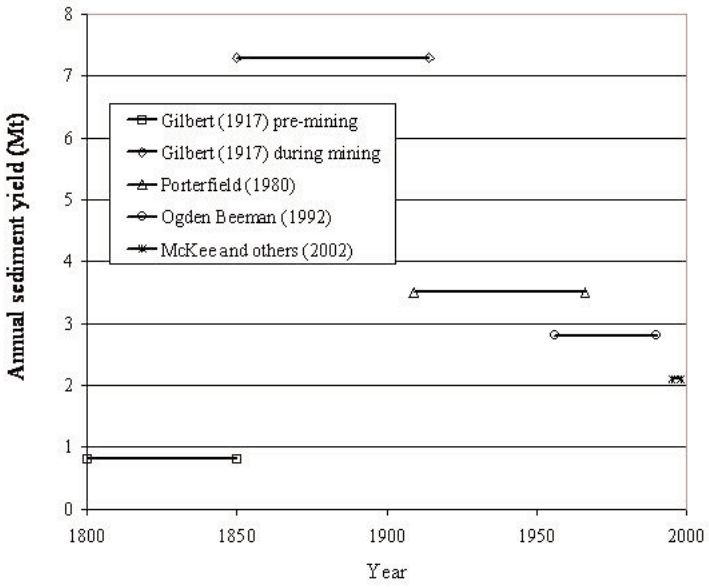

Figure 2. Results of several previous studies of sediment yield to San Francisco Bay, California, showing the increase due to hydraulic mining and subsequent decrease (Mt is million metric tons).

dams and reservoirs, levees and riverbank protection, and logging. A discussion of each of these activities and their potential effects on sediment yield is provided in the "Discussion" section on page 9.

Over the past 200 years, tidal marsh area in San Francisco Bay has decreased by 79% due human activities (Goals Project 1999). Large areas of the Sacramento-San Joaquin Delta were leveed and turned into highly productive agricultural "islands." Recently, a group of California state and federal agencies (CALFED, http://calwater.ca.gov/) has been charged with improving the quality and reliability of California's water supplies and reviving the San Francisco Bay-Delta ecosystem. One alternative being considered for improving the ecological health of the estuary is restoring tidal action to some historic tidal marsh areas. However, land subsidence within the Delta and forecasted rising sea-level dictate that adequate sediment supply for deposition is crucial for restoring these areas to elevations typical of tidal marshlands. Thus, the sediment supply and location of deposition are critical factors for identifying potential restoration sites and determining the success of each project. Addressing the sediment supply to the bay and delta in the context of CALFED restoration objectives was the primary motivation for this study.

FLOW AND SEDIMENT DATA RECORDS

The U.S. Geological Survey (USGS) monitored daily flow and suspended-sediment discharge on the Sacramento River just upstream of the delta for water years 1957 through 2001. All data used in this study were taken from three USGS databases (USGS 2001a, 2001b, 2001c). The gage was moved from I Street in downtown Sacramento (USGS gage 11447500) to Freeport (USGS gage 11447650) following water year 1979 (Figure 1). The Freeport gage is about 21 river kilometers downstream from the American River confluence (near I Street) in Sacramento. Figure 3 shows the daily records of flow (Q, m^3 sec^{-1}), suspended-sediment discharge (Q_s, kg sec^{-1}), and discharge-weighted cross-section average concentration ($C = Q_s/Q$, mg L^{-1}) respectively. No significant shift in the records occurred after the gage was moved because no major tributaries enter between the two locations. Visual inspection of the daily records revealed no obvious trend in flow, but revealed possible decreasing trends in suspended-sediment discharge and concentration.

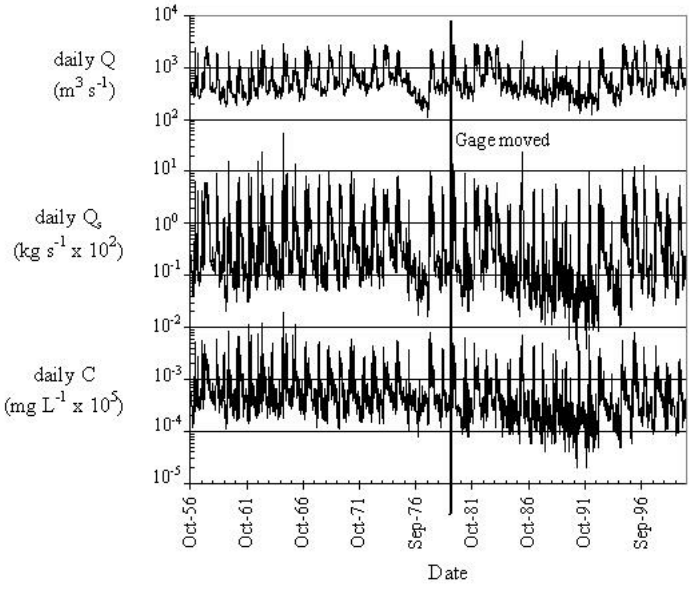

Figure 3. Daily flow (Q), suspended-sediment discharge (Q_s), and concentration (C) for the Sacramento River at Sacramento/Freeport. Note that Q_s and C were scaled to separate the records vertically.

Figure 3 illustrates that the annual cycle of wet and dry seasons is altered by climate-induced multi-year droughts. Flow was greatest during the winter months when precipitation was greatest, and low during the dry season from spring to autumn. Droughts in 1976 – 1977 and 1987 – 1992 that reduced flows and suspended-sediment discharge followed a similar pattern (Figure 3). In addition, the Yolo Bypass (constructed in the early 1930s to route floodwaters around Sacramento), removed floodwaters from the Sacramento River upstream from the gage (see Figure 1) during some winters, and thus effectively limited the maximum flow past the gage to about 3,000 m^3 sec^{-1}. To provide analysis of the flow record upstream from the bypass, the flow at Sacramento/Freeport was summed with flow at the Yolo Bypass near Woodland (USGS gage 11453000) and flow over the Sacramento Weir (USGS gage 11426000). Though the flow at Woodland included some water not derived from the Sacramento River, comparison with the spill over the Fremont Weir (USGS gage 11391021) indicated that the difference is minimal. The Fremont Weir spill data were not used directly because the gage was discontinued in 1975. Travel time between the gage locations was not accounted for; rather the three records were summed on a daily basis. This had little effect on the annual totals, which is the primary use of the data.

The suspended-sediment discharge and concentration data shown in Figure 3 are daily averages. The daily suspended-sediment discharge was computed from individual concentration measurements and flow measurements, based on procedures from Guy and Norman (1970). The procedures essentially entail using periodic concentration measurements with the flow record (typically hourly) to approximate a continuous record of concentration, which then is used to develop the daily record. The uncertainty and error that is inherent in estimating concentration from flow, as well as possible changes in the frequency of concentration measurements, leads to the possibility of an artificial trend in the daily records. Therefore, the record of individual concentration measurements also was analyzed for time trends. These data are plotted in Figure 4, where a decreasing trend in concentration is clearly evident. However, these measurements were extracted from several databases and include measurements made by various methods for various purposes. For example, it is typical for a concentration measurement to be made frequently at a single vertical section (i.e., daily observer samples), and then related to the cross-section average concentration using less frequent (e.g., monthly) equal-discharge-increment measurements. The concentrations include both frequent and infrequent measurements, but Figure 4 shows that the frequent single vertical measurements dominate the time series, except for two time periods (1957–1972 and 1983–1987) when these measurements either were not taken or, more likely, not entered into the database.

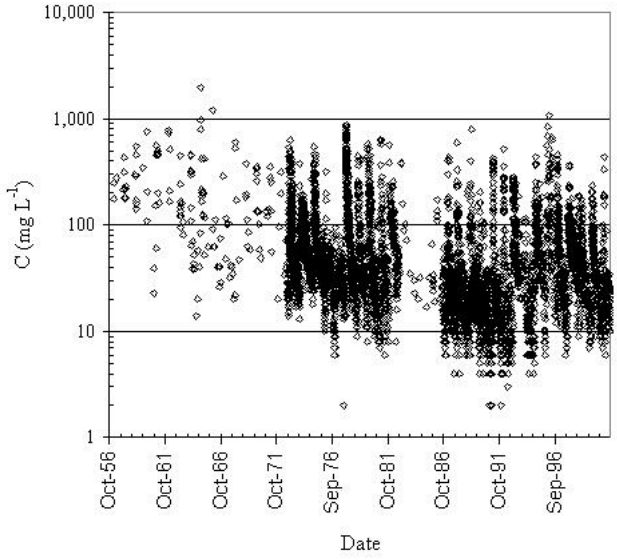

Figure 4. Record of individual concentration measurements (*C*) for the Sacramento River at Sacramento/Freeport. Concentrations in Figure 3 are daily averages.

To summarize, the following data records were used in the analysis: (1) daily flows at Sacramento/Freeport (gage 11447500 for 1957–1979; gage 11447650 for 1980–2001); (2) daily flows upstream of the Yolo Bypass (sum of flow at Sacramento/Freeport and gages 11453000 and 11426000); (3) daily suspended-sediment discharge at Sacramento/Freeport (gage 11447500 for 1957–1979; gage11447650 for 1980 – 2001); and (4) individual concentration measurements at Sacramento/ Freeport (11447500 for 1957–1979; 11447650 for 1980–2001).

Only suspended-sediment discharge has been measured for the period of record analyzed here and it is

assumed that trends in suspended load are indicative of overall trends in sediment yield. This assumption is supported by evidence that suspended-sediment transport dominates bedload in the lower Sacramento River. Porterfield (1980) estimated that bedload transport (or, more accurately, unmeasured transport; see reference for details) accounted for 13% of the total transport at the Sacramento gage (11447500) for the time period 1957–1966, using the daily suspended-sediment discharge data and modified Einstein procedure (Colby and Hembree 1955). Also, Dinehart (2002) investigated bedform transport mechanics near the Freeport gage using bedform-mapping techniques. Bedload transport rates (or, more accurately, bedform transport; see reference for details) for several time periods between July 1998 and April 2000, including a period of high flow in January 2000, were only 1% to 2% of the total transport.

DATA ANALYSIS AND RESULTS

Two statistical tests were used to determine the statistical significance of monotonic time trends. Kendall's τ and Spearman's ρ are non-parametric correlation coefficients that measure the correlation between two continuous variables (Helsel and Hirsch 1992), such as time and sediment yield. To determine the statistical significance of a trend, the computed coefficients were compared to what would be expected entirely due to chance. Therefore, the correlation coefficients cannot provide concrete evidence of a trend but, rather, the probability of a trend.

Flows

Annual records of flow and suspended-sediment discharge were computed by summing the daily records shown in Figure 3 for each water year. The annual records, including the annual concentration (annual sediment discharge divided by the annual flow at Freeport), are shown on Figure 5.

Because sediment discharge is correlated with flow, the flow records first were analyzed for time trends. The annual sediment discharge could be affected by either a change in annual flow (e.g. due to water exports) or a change in the variability of the flow record (e.g. due to reservoir regulation). For example, sediment discharge and flow can typically be related as follows:

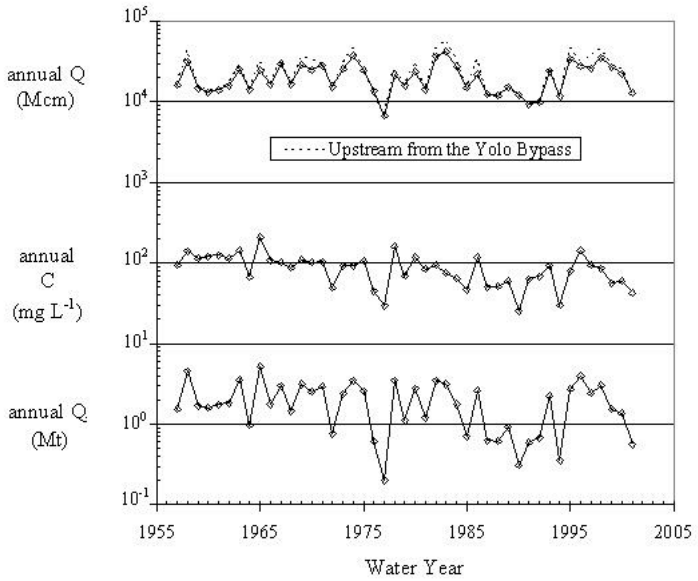

Figure 5. Annual flow (Q), suspended-sediment discharge (Q_s), and concentration (C) for the Sacramento River at Sacramento/Freeport (Mcm is million cubic meters, Mt is million metric tons).

$$Q_s = aQ^b \qquad (1)$$

where Q_s is sediment discharge, Q is flow, and a and b are empirical constants. The coefficient b typically is greater than unity (e.g., Vanoni 1975) so that, for example, if the frequency of high flows decreased and the frequency of low flows increased (i.e., same mean, less variance), the total annual sediment discharge would decrease.

The annual flow records at Sacramento/Freeport and upstream of the Yolo Bypass were analyzed to test for changes in total water yield. To check for changes in flow variability, the quartiles of the daily flow record (representing the minimum, 25% exceedence, median, 75% exceedence, and maximum flows) were determined (Figure 6). The only significant difference in quartiles between Sacramento/Freeport and upstream of the bypass was for the maximum flows and, thus, it is the only one shown on the figure for both locations. Visual inspection of Figure 6 does not reveal any obvious systematic trends in flows over the entire period 1957–2001, though shorter-term, climate driven, wet and dry periods are apparent. Results of the statistical tests for flows are given in Table 1.

Table 1. Results of statistical trend tests for flows (Q) on the Sacramento River at Sacramento/Freeport and upstream from the Yolo Bypass, California, 1957–2001. [Results (p-values) are expressed as the probability (as a percentage) that a trend exists. (↑)(↓), arrows indicate the direction of the trend].

Record	*Location*	*Kendall's* τ	*Spearman's* ρ
Annual Q	Sacramento/Freeport	24 (↓)	20 (↓)
Minimum daily Q	Sacramento/Freeport	42 (↓)	53 (↓)
25th percentile daily Q	Sacramento/Freeport	62 (↑)	61 (↑)
Median daily Q	Sacramento/Freeport	41 (↑)	51 (↑)
75th percentile daily Q	Sacramento/Freeport	48 (↓)	42 (↓)
Maximum daily Q	Sacramento/Freeport	1 (↑)	6 (↑)
Maximum daily Q	Upstream from the Yolo Bypass	38 (↓)	41 (↓)

The results indicate that there are no significant trends over the period 1957–2001 in either annual flow or the variability of the flow record, if typical significance levels are used (e.g., $p < 0.05$ or $p < 0.01$, or equivalently a trend probability of >95% or >99%, respectively). Flood control/irrigation reservoirs in the system might be expected to reduce peak flows and increase low flows. However, two of the major reservoirs in the system, Shasta and Folsom dams, were constructed prior to the beginning of the flow record. The other major impoundment in the watershed, Oroville Dam, was completed during the study period (1968) but is downstream of Lake Almanor Dam, another significant impoundment constructed much earlier (1927).

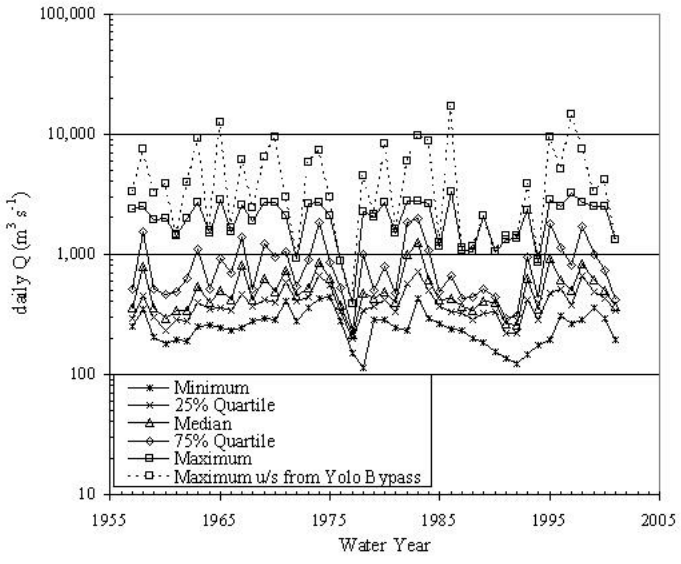

Figure 6. Annual quartiles of daily flow (Q), Sacramento River at Sacramento/Freeport and upstream from the Yolo Bypass (maximums only).

Suspended-sediment Discharge

Because there have been no significant changes in the flow record over the period 1957–2001, any trends in sediment yield must be related to factors that are independent of flow. Trends in annual suspended-sediment discharge were analyzed by first separating the records into ranges of flow, which factors out the annual variability in flow and allows for the comparison of annual sediment discharge under similar flow conditions. Ideally, the record would be separated into narrow bands of flow, however, the sample size of the annual record (n = 45 years) limits the number of practical flow ranges. Thus, only two ranges were used, the upper and lower 50% of annual flows (Figure 7). A clear, decreasing trend is evident for each flow range. The results of the statistical tests are given in Table 2.

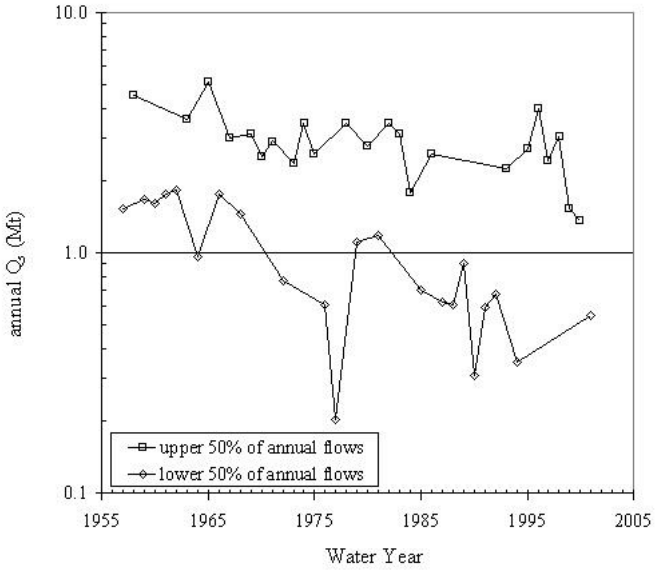

Figure 7. Annual suspended-sediment discharge (Q_s) for the upper and lower 50% of annual flow, Sacramento River at Sacramento/Freeport.

Table 2. Results of statistical trend tests for annual suspended-sediment discharge (Q_s) on the Sacramento River at Sacramento/Freeport, California, 1957–2001. [Results (p-values) are expressed as the probability (as a percentage) that a trend exists. (↑)(↓), arrows indicate the direction of the trend].

Suspended-sediment Record	*Kendall's* τ	*Spearman's* ρ
Annual Q_s, all flows	92 (↓)	93 (↓)
Annual Q_s, upper 50% of flows	>99 (↓)	>99 (↓)
Annual Q_s, lower 50% of flows	>99 (↓)	>99 (↓)

Results of the two statistical trend tests indicate a very high probability (>99%) of a decreasing trend in annual suspended-sediment discharge for a given range of annual flows. The probability of a trend is lower (93%) when the entire record of suspended-sediment discharge is used, due to the annual variability in flow.

Trends in suspended-sediment discharge also may be detected by analyzing the daily records. Because there are no significant changes in flow variability, analysis of the daily records should give similar results to the annual records. If the flow variability were changing, for example becoming less variable, then the daily suspended-sediment records would provide an analysis that was independent of the changes in flow. Nonetheless, analysis of the daily records can provide further evidence that suspended-sediment discharge, for a given flow, is decreasing with time. As with the annual suspended-sediment discharge records, the daily records were separated into ranges of flow. The increased sample size allows for the use of ten increments instead of two. Data for three of the flow ranges are plotted in Figure 8. A decreasing trend in daily suspended-sediment discharge for each flow range is apparent in the figure. As expected, the statistical tests indicate a very high probability (>99%) of a decreasing trend in daily suspended-sediment discharge for all ranges of flow.

Individual Concentration Measurements

As discussed previously in this paper, changes in the methodology for computing daily suspended-sediment discharge with time could result in an artificial trend in the daily record. To address this, the record of individual concentration measurements also was analyzed (Figure 4). Because the concentrations exhibit a correlation with flow, the record was separated into 10 percentile increments of flow. The individual concentration measurements were not always accompanied by an instantaneous flow measurement; thus daily flow records were used for separating the concentration measurements. Figure 9 shows the concentration measurements for two of the flow ranges. Visual inspection

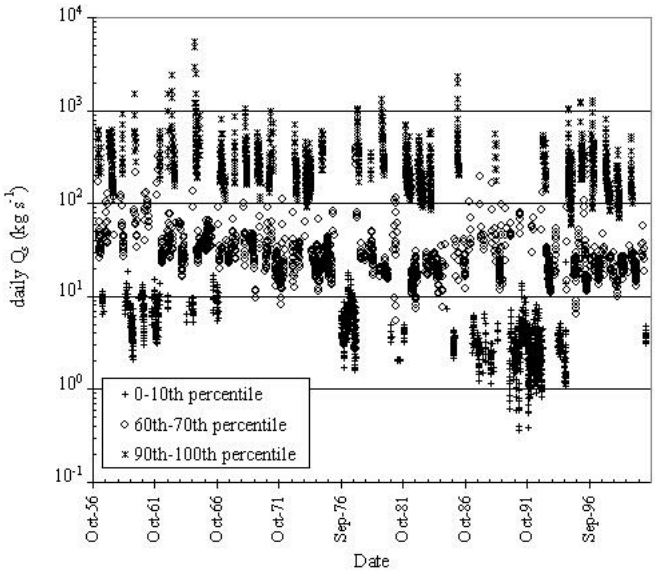

Figure 8. Daily suspended-sediment discharge (Q_s) for the 0 to 10th, 60th to 70th, and 90th to 100th percentile ranges of flow, Sacramento River at Sacramento/Freeport.

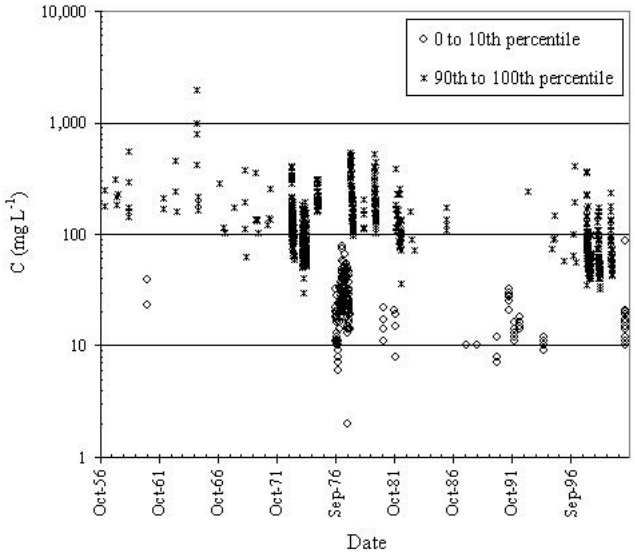

Figure 9. Individual concentration measurements for the 0 to 10th and 90th to 100th percentile ranges of flow, Sacramento River at Sacramento/Freeport.

indicates a clear decreasing trend in concentration. As with the daily sediment discharge record, the statistical tests indicate a high probability (>99%) of a decreasing trend for all discharge ranges.

Major Flood Events

Finally, further evidence for a trend of decreasing sediment yield was found by examining the daily concentration records for several major floods during the period of record. Figure 10 shows the six highest daily flow peaks (upstream from the Yolo Bypass) versus the corresponding daily concentration since the gage was established at the beginning of water year 1957. The flows upstream from the Yolo Bypass are shown because they are more indicative of extreme flood conditions than the flow at Sacramento/Freeport, which is controlled by the spill to the Yolo Bypass. The floods of 1963 and 1964 resulted in higher sediment concentrations at Sacramento/Freeport than the similar peak flow events of 1970, 1986, 1995, and 1997. However, peak concentration is not solely a function of peak flow. Other factors, such as hydrograph shape (particularly the steepness of the rising limb) and antecedent sediment conditions, may result in a different peak concentration for the same peak discharge.

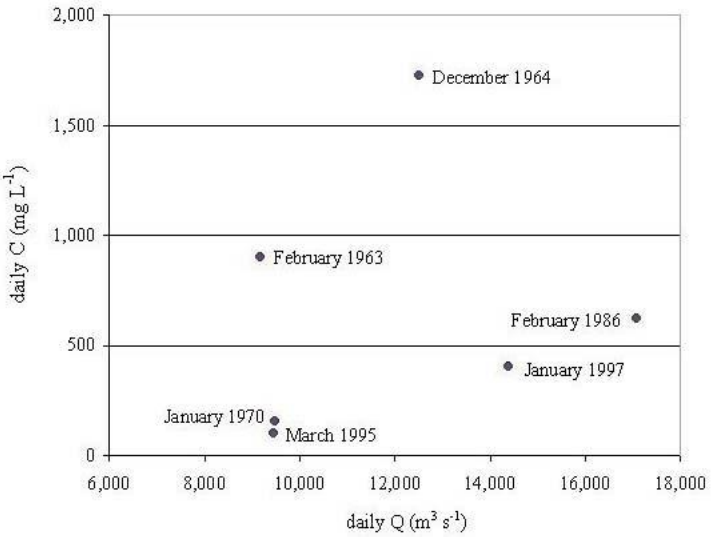

Figure 10. Peak daily flow (*Q*) and concentration (C) for the largest Sacramento River flood events since water year 1957. Flows are upstream from the Yolo Bypass, concentrations are at Sacramento/Freeport.

These factors are investigated by more closely examining the three highest flow peaks of record: the floods of 1964, 1986, and 1997. Note that the greatest peak concentration was in 1964, despite the smaller peak flow. The effect of antecedent watershed sediment conditions should be roughly similar for each flood because another significant flood occurred within two to three wet seasons prior to each flood. This suggests that differences in the peak concentration in 1964, 1986, and 1997 are not the result of a flush of sediments that may have built up in the watershed during extended periods of low flow.

The effect of hydrograph shape is analyzed by plotting the hydrographs and daily concentration records shown in Figures 11 and 12 (note the flow peaks are centered at day 100, for comparison). Figure 11 shows that the Yolo Bypass had similar flows during each of the floods. Figure 12 shows the large difference in peak concentration at Sacramento/Freeport between the three floods. There are small differences in the shapes of the hydrographs, including the steepness of the rising limb and the number and magnitude of smaller flow peaks preceding the main peaks. However, the hydrographs are remarkably similar in shape, yet there is a significant decrease in peak sediment concentration from 1964 to 1986, and again from 1986 to 1997.

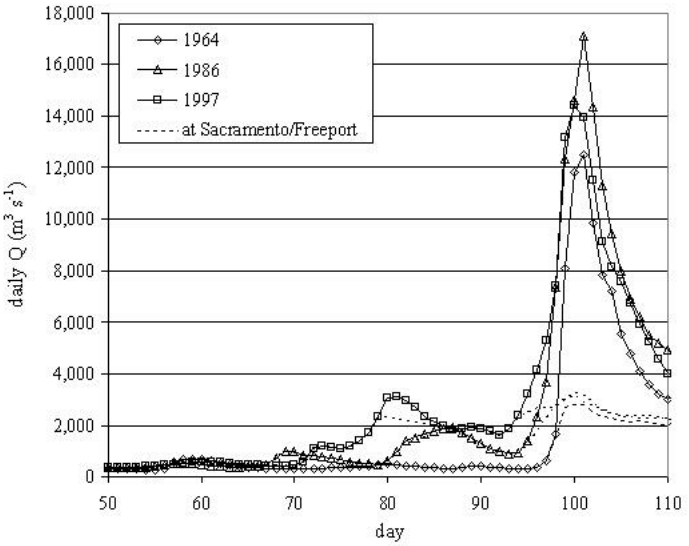

Figure 11. Daily flows (*Q*) on the Sacramento River for the floods of 1964, 1986, and 1997. Symbol records are for upstream from the Yolo Bypass; dashed lines are for Sacramento/Freeport.

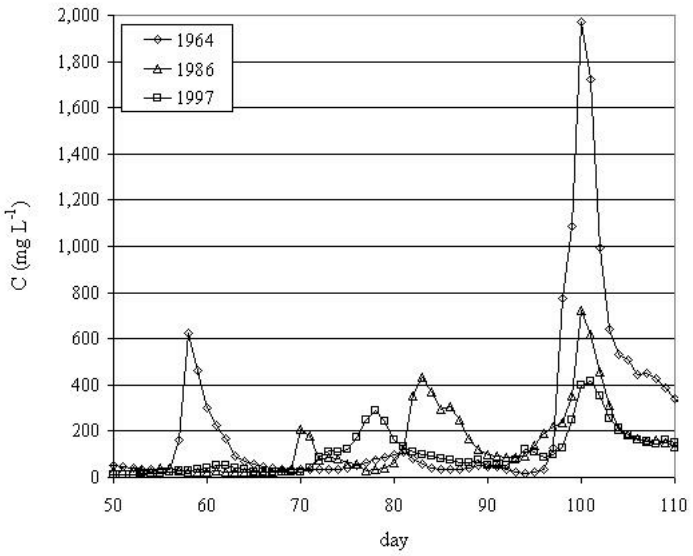

Figure 12. Daily concentration (C) on the Sacramento River upstream from the Yolo Bypass for the floods of 1964, 1986, and 1997.

Given the number of factors that influence the relationship between flow and concentration, including the timing and size of previous floods, hydrograph shape, antecedent soil conditions, rainfall versus snowmelt, etc., it is not suggested here that the data presented in this section alone is conclusive evidence for a decreasing trend in sediment yield. However, combined with the trend analyses presented in the previous two sections, the most logical explanation for the differences in peak concentration seems to be reduced sediment yield from the watershed. If the differences in peak concentration were explainable due to some other factor, this would not change the conclusions of this paper.

DISCUSSION

The trend of decreasing suspended-sediment discharge in the Sacramento River identified in this paper could be the result of several disturbances in the watershed, including historic hydraulic mining, dams and reservoirs, levees, bank protection, logging, and conversion to agricultural and urban land uses. Table 3 lists each of these disturbances and the expected responses of sediment yield, which are discussed subsequently.

One potential cause of the trend that can be immediately eliminated is the Yolo Bypass. Since the bypass extracts large amounts of water upstream from the Sacramento/Freeport gage during high flows, it is also expected to extract some amount of suspended-sediment as well (though this amount is not well known). If the amount of sediment being extracted by the bypass were for some reason changing over time, then this could lead to a trend in suspended-sediment discharge at Sacramento/Freeport. However, the analysis indicates that the sediment yield is decreasing even for the low flow ranges (annual and daily) when there is no spill to the bypass. This eliminates the Yolo Bypass as a potential cause of the trend.

Table 3. Summary of disturbances potentially affecting Sacramento River sediment yield.

Watershed Disturbance	*Expected Effect on Sediment Yield*
Hydraulic mining	Increase[a]
Dams and reservoirs	Decrease
Levees and isolation of the floodplain	Increase
Bank protection	Decrease
Conversion to agricultural and urban land uses	Increase
Logging	Increase

[a] During mining, sediment yield increases. Following cessation of mining sediment yield decreases, possibly to pre-mining levels.

Hydraulic mining probably has been the single greatest disturbance affecting sediment yield in the Sacramento River watershed. Gilbert (1917) details the practices and their effects on sediment transport. Hydraulic gold mining introduced large quantities of silt, sand, and gravel into the Sacramento River system during the late 1800's, particularly through the major westerly flowing tributaries, such as the American, Feather, Yuba, and Bear Rivers. Following the cessation of hydraulic mining in 1884, sediment yield would be expected to gradually decrease to levels existing before mining, assuming all other factors remained the same. Thus, it is plausible that the decrease in sediment yield was the result of hydraulic mining-derived sediment that continued to move slowly through the system. Gilbert estimated that the effects of the mining would continue for approximately 50 years after 1914, and it has been shown that the main pulse of bed sediment passed Sacramento prior to 1950 (Meade 1982). Further, the delivery of the mining tailings from the tributary upper watersheds to the Sacramento River

has been reduced significantly (if not eliminated) by the construction of several large dams on the major tributaries. However, James (1991) reported that large volumes of tailings remain stored on the Bear River floodplain downstream of the most downstream dam (Camp Far West). Such deposits still may be eroded and transported to the Sacramento River, and the depletion of such deposits as the rivers adjust to dynamic equilibrium could result in a decrease in sediment yield with time.

Along with the depletion of stored hydraulic mining sediment, dams and reservoirs have the potential to significantly reduce the sediment yield from the Sacramento River watershed. Several large dams and reservoirs have been constructed on the Sacramento River and its tributaries. Shasta Dam on the upper Sacramento River, Oroville Dam on the Feather River, and Folsom Dam on the American River are three of the largest dams in California. Dams can have several effects on sediment transport dynamics, both upstream and downstream. First, dams trap sediment by decreasing the river flow velocity upstream and inducing deposition. This trapping cuts off a supply of sediment that would be deposited on the valley floor or delivered to the watershed outlet. Second, because reservoir releases contain little or no sediment, the relatively clear, released water erodes the downstream channel in an attempt to equilibrate with the new upstream supply. Because the new upstream supply is near zero, the channel will tend to incise, widen, and armor the bed, which reduces bed shear stress and sediment transport capacity. Alternatively, reduced sediment transport capacity may be achieved by vegetation encroachment resulting in channel narrowing. However, for one of the major impoundments in the system, Oroville Dam, Porterfield and others (1978) found significant channel enlargement and concluded that channel adjustments were still in progress in 1978 (dam constructed in 1967). Finally, reservoir releases are less variable than natural flows, i.e., the peak flows are stored in the reservoir for flood control, irrigation, and water supply. Because the majority of sediment transport occurs during high flows, reducing the magnitude of these flows reduces the total sediment transport capacity downstream. However, analysis of the flow record in the "Flows" section of this paper (p.5) indicated no significant change in flow variability, possibly because several of the large dams were in place prior to the beginning of the record.

The amount of sediment trapped by a dam can be computed by examining successive reservoir surveys and determining the change in storage volume with time. Three large dams in the Sacramento River watershed, Oroville, Folsom, and Englebright dams, were resurveyed recently. The Lake Oroville survey in 1994 yielded an estimate of 22 million cubic meters (Mcm) of total deposition since the construction of the dam in 1967 (CDWR 2001). Assuming a specific dry weight of the sediment deposit of 1,121 kg m^{-3} (typical for fine sand and silt, Vanoni 1975), the total mass of deposition between 1967 and 1994 was about 25 million metric tons (Mt). A 1991 resurvey of Folsom Lake yielded an estimate of 41 Mcm of deposition (46 Mt) since construction in 1956 (USBR 1992). Finally, Englebright Dam on the Yuba River has accumulated about 21 Mcm of sediment (22 Mt) since construction in 1941 to 2001 (Childs and others 2003). These data are summarized in Table 4 below.

Table 4. Sedimentation rates for three large reservoirs in the Sacramento River watershed [Mcm is million cubic meters; Mt is million metric tons. Mass of deposit assumes a specific dry weight of 1,121 kg m^{-3}].

			Total Deposition from Construction to Resurvey	
Dam/ Reservoir	***Year Constructed***	***Year Resurveyed***	***Volume (Mcm)***	***Mass (Mt)***
Oroville	1967	1994	22	25
Folsom	1956	1991	41	46
Englebright	1940	2001	22	25

To evaluate the order of magnitude of the deposition shown in Table 4, consider the approximate decrease in annual suspended-sediment discharge. The annual records shown on Figure 5 suggest a decrease in average annual suspended-sediment yield from about 2 to 3 Mt in 1957 to about 1 to 2 Mt in 2001. Assuming the decrease is approximately linear, this corresponds to a total decrease in sediment yield of about 25 Mt, compared to the yield if the discharge had not decreased during this period. Thus it is seen that the deposition in

Oroville, Folsom, and Englebright (25, 46, and 22 Mt, respectively) is of the same order of magnitude, and indeed the total mass from all three reservoirs is significantly greater than the decrease seen at Sacramento/Freeport (25 Mt). There are several possible explanations for this finding. First, the mass of deposition in the reservoirs is a rough estimate due to the assumed specific weight of the deposits. Also, the reservoir deposits consist of both bedload and suspended-sediment, while the decrease estimate is for suspended-sediment only. Further, some of the suspended-sediment that is trapped in the reservoirs would likely be deposited on the valley floor and thus not contribute to sediment yield. Erosion of material downstream from dams could also partially compensate for the difference. Finally, the 25 Mt estimated decrease assumed a constant annual yield at the 1957 level through 2001. Given that only three reservoirs are trapping such a high volume of sediment and that there are reservoirs upstream of these and on other tributaries in the system, it is possible that sediment yield may have in fact been increasing during this period in the absence of the reservoirs. The fact that the deposition reflects only a small percentage of the reservoir capacity (Oroville ~0.5%, Folsom ~3%, Englebright ~25%) reflects the size of the reservoirs, and should not be construed as evidence that the reservoirs are not affecting the sediment yield.

Finally, a comment must be made regarding the gradual decrease in annual suspended-sediment discharge (Figure 5). One might expect reservoirs to have a more immediate effect on sediment yield, as the sediment source is cut off immediately when the dam is closed. Following dam closure, however, erosion of the downstream channel will compensate partially for the decrease in upstream supply. But as the channel adjusts toward a new equilibrium, the erosion and, thus, sediment yield will gradually decrease. Porterfield and others (1978) have documented this process for the Feather River below Oroville Dam.

To minimize the risk of levee and bridge failures, bank protection measures such as riprap also have been implemented in many locations and are expected to decrease sediment yield. In regions of active channel meandering, such as the middle Sacramento River (Brice 1977), bank stabilization eliminates a source of sediment (the channel banks).

In contrast to reservoirs, bank protection, and the depletion of stored hydraulic mining sediment, other anthropogenic influences in the watershed may increase sediment yield. Settlement has produced an extensive network of levees for flood protection. Under pre-settlement conditions, the Sacramento River watershed contained several large flood basins that were adjacent to the main channel (Bryan 1923). During floods, these basins would fill with water, allowing some of the sediment in the floodwaters to deposit on the floodplain. The levees have isolated these basins from the river channel and, therefore, eliminated a sediment sink. Furthermore, by confining the floodwaters to the river channel, levees typically increase peak water level, flow velocity, and bed shear stress, resulting in increased sediment transport capacity. Even the bypass flood channels in the watershed such as Yolo are leveed and much smaller that the natural flood basins. For these reasons, the levees would be expected to increase the annual sediment yield.

The past 150 years have seen significant changes in land use throughout the Sacramento River watershed that have the potential to increase soil erosion and sediment yield. The conversion of the valley floor to primarily agricultural and grazing land use has the potential to introduce increased amounts of sediment to the river systems due to soil tillage and livestock disturbance. Urbanization can also affect sediment yield by affecting the flow hydrograph (impervious surfaces increase peak flows because infiltration is zero) and thus the sediment transport capacity. Finally, logging and land development in the Sierra Nevada and foothills have the potential to increase sediment yield due to soil disturbance, increased runoff, road construction, etc. Based on these qualitative observations, it is expected that land use changes would result in an increase in annual sediment yield.

To summarize, the factors affecting sediment yield are listed in Table 3. Several factors have the potential to increase sediment yield, while several others have the potential to decrease sediment yield. The decreasing trend in suspended-sediment yield from 1957–2001 indicates that the factors resulting in decreased yield dominated during this time period. These factors include reservoir sedimentation, bank protection, and the depletion of stored hydraulic mining derived sedi-

ments. The future sediment yield of the Sacramento River watershed is dependent on the future balance between these competing factors.

CONCLUSIONS

Analysis of daily flow and suspended-sediment discharge data for the lower Sacramento River for the time period 1957–2001 yielded the following main conclusions.

- Statistical tests indicate a very high probability (>99%) of a decreasing trend in suspended-sediment discharge for a given flow. The annual suspended-sediment yield has decreased by about one-half over the time period.
- Peak concentrations during the largest floods of the time period also appear to have decreased with time, corroborating the finding of decreasing suspended-sediment discharge.
- In contrast, statistical tests indicate no overall time trend in annual flow or flow variability, though shorter-term climatic variability is apparent. This is likely due to the fact that several large dams were in existence in the watershed prior to the beginning of the time period analyzed here (1957).
- Three large reservoirs in the watershed have accumulated a mass of sediment of the same order of magnitude as the decrease in suspended-sediment yield over the time period of study. The decrease in sediment yield may be due to reservoir sedimentation and the associated adjustment of channels downstream from the dams.
- Along with reservoir sedimentation, bank protection measures and the gradual depletion of stored hydraulic mining derived sediments have the potential to decrease sediment yield. Several other factors, such as levees, logging, urbanization, agriculture, and grazing have the potential to increase sediment yield. The future sediment yield will depend on the future balance between these competing factors.

The findings presented here have clear implications for CALFED restoration planning in the Sacramento-San Joaquin Delta and San Francisco Bay. It may not be appropriate to assume that the sediment yield to the delta will be the same 50 years from now as it is today. The trend may be approaching a post-settlement equilibrium sediment yield for the watershed (Figure. 2), assuming the factors affecting sediment yield remain relatively unchanged into the future. However, it is not possible at this time to project the sediment yield trend without more knowledge of the physical mechanisms, such as the trapping efficiency of the reservoirs and the effects of agriculture and grazing on soil erosion. Climatic variability and climate change also have the potential to affect future sediment yield. More detailed studies are required to better quantify the magnitude of each effect on sediment yield, and thus allow for a more constrained prediction of sediment yield into the future.

In a broader context, the study indicates the need to address anthropogenic effects within the watershed when considering management decisions (e.g., ecological restoration) in downstream depositional areas, such as estuaries. For the case of restoring tidal wetlands, it may seem logical to assume that if anthropogenic barriers are eliminated (i.e., dikes and levees), previously tidal areas will return to their pre-disturbance geomorphic forms. However, since the pre-disturbance tidal geomorphology was linked to the pre-disturbance sediment supply, the significant change in the sediment supply may result in a much different equilibrium estuary geomorphology and restored areas may not return to their pre-disturbance condition.

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