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New methods for estimating annual and long-term suspended sediment loads from small tributaries to San Francisco Bay

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Abstract Estimates of suspended sediment loads entering San Francisco Bay (California, USA) have been generated in the past by a number of researchers. Recently, it has been confirmed that the loads entering the Bay from the Central Valley are decreasing over time; as such, the loads from small local tributaries may constitute an increasing component of the overall Bay sediment budget. Previous estimates of suspended sediment loads entering San Francisco are outdated because of the wealth of new data, evolving land uses, and the availability of new methods of analysis. Our report presents updated estimates of suspended sediment loads entering San Francisco Bay from local tributaries. This information is essential for developing management strategies for many surface-reactive pollutants (e.g. certain trace metals and hydrophobic organic pollutants). In our study, we explore and evaluate hydrological, physical, and land-use characteristics of the San Francisco Bay watersheds to predict relationships between watershed sediment loads and geomorphic processes, and ultimately, to provide an updated estimate of regional suspended sediment loads from small tributaries. Based on this analysis, peak flow explained most of the variability in the sediment loads. Measured annual suspended sediment loads in Bay Area watersheds vary inter-annually by two to four orders of magnitude. Regionally, the new discharge- and land-use-based estimate of contemporary average annual suspended sediment loads entering the Bay is 1 300 000 t. This is equivalent to an average of 155 t km^{-2}. It is estimated that 35% of this load is associated with mostly urbanized watersheds.

Key words sediment budget; fluvial geomorphology; sediment transport

INTRODUCTION

Information on suspended sediment loads is of paramount importance in the management of urbanized estuaries because of linkages to the degradation of water and sediment quality, recreational amenities, native species habitat, and disruption of commercial shipping operations. The San Francisco Bay (California, USA) aquatic ecosystem has deteriorated over the past century in response to the pressures of human population growth, reclamation of wetlands, resource extraction, and agriculture. In San Francisco Bay, accurate information about sediment loads is critical because: (1) sediments can be pollutants in themselves, degrading riparian habitat through siltation; (2) sediments carry particle-associated pollutants, such as Hg, PCBs, and legacy organochlorine pesticides; (3) sediment annually has to be dredged from shipping channels; and (4) sediment budgets in different segments of the Bay are critical for predicting the accretion rate in restored tidal wetlands. Understanding the sources of sediments in specific areas of the Bay could assist in resource planning and in focusing management measures. For these reasons, it is essential to have accurate information about how much sediment enters the Bay, where it enters the Bay, and how much originates from urbanized *vs* non-urbanized areas.

Estimates of suspended sediment loads entering San Francisco Bay have been presented by a number of researchers. These authors used a variety of quantitation methods; for example, total basin deposition (Gilbert, 1917) or various sediment rating curve methods using either daily or annual discharge (Krone, 1979). Previous authors had to make some grossly simplifying assumptions to develop regional scale suspended sediment load estimates. In particular, previous authors did not distinguish between urban and non-urban land use. In addition, these estimates may be considered outdated because of the wealth of new data collected by the US Geological Survey (USGS). Some reports argue that suspended sediment loads entering the Bay from the Central Valley via the Delta should decrease over time (Krone, 1979). Thus, loads from small local tributaries may be increasingly important in delivering suspended sediment from the Central

Valley. It is currently estimated that approximately 40% of the total suspended sediment load entering the Bay may derive from small urbanized or urbanizing tributaries, these represent less than 5% of the Bay's total watershed area.

METHODS

Using statistical methods, we estimate sediment inputs into San Francisco Bay from local watersheds (8180 km^2) (areas draining directly to the California coast, and wetland areas on the Bay margins that are physically separated from tributaries are excluded from this analysis). The estimates are expressed as long-term annual averages. The same method also allowed estimation of the inter-annual variations within the basin.

Precipitation and streamflow are critical components for determining the magnitude of suspended sediment loads. Our study was based on the streamflow and sediment discharge characteristics of 29 gauged watersheds (2.0–1639 km^2). The Bay Area climate is Mediterranean, with 95% of the precipitation taking place during the winter. The annual precipitation in the study area varies from 300 mm to more than 1500 mm. Some of the gauged watersheds in the Bay Area have one or more dams that together are downstream from drainage areas totalling 1600 km^2. In general, downstream sections of watersheds adjacent to the Bay are highly urbanized, while natural (open space) and agricultural land use areas are mostly in the upstream sections of the watersheds. At the scale and scope of the present investigation it was impossible to investigate detailed historical loads. Like previous authors, we assume steady state (no trend in the discharge and suspended sediment data sets) for the period of data collection in non-urban areas (1957–2007). This is reasonable if we assume the greatest forcing factors are landscape erodability (geology, soils, climate, tectonic activity). In the study area all the dams were built before the sediment load data were collected, and most agricultural land is used for grazing; therefore, it is less susceptible to new agricultural BMPs.

Regression analyses were performed between the individual spatial parameters and measured annual suspended sediment loads to test the ability of individual parameters to explain the variation in the suspended sediment load. In this analysis, urban land use explained little of the variation in sediment loads in Bay Area watersheds. This is because urban land use was not sufficiently sampled in the different geomorphic provinces to be used as an independent variable, not because urban land use yields similar sediment loads to other land uses. Thus, it was necessary to classify Bay Area watersheds as mainly urban or non-urban, before applying a specific sediment load estimation method to each class.

Flow-based method

In the study area, most of the gauging stations monitor watersheds dominated by natural or agricultural land use. The local rivers produce the majority of flow and sediment discharge during intense winter storms. On average, half of the annual discharge and ~90% of the sediment load occurs during only a few days per year (Kroll, 1975). Suspended sediment loads mostly derived from non-urban watersheds were estimated by applying local empirical statistical relationships between sediment loads and various physical characteristics of the gauged watersheds. We found that for non-urban watersheds, annual peak discharge correlated with annual sediment load better than annual total flow or any other independent variable.

Peak discharge is related to sediment load using a power function (Leopold & Wolman, 1956; Mueller & Foerstner, 1968):

$$Q_s = aQ_p^b \tag{1}$$

where Q_s represents sediment load, Q_p represents peak discharge, and a and b represent watershed-specific parameters (a is a function of the sediment supply; b represents the erosive power of the water discharge; both a and b are constants that are unique to each watershed and together scale water discharge to suspended sediment loads).

These parameters are also dependent on land use, climate, hydraulics, and particle size distribution (80% of particles are in the silt and clay fractions).

For this study, the Bay was divided into the same geomorphic provinces used by Rantz (1971): East Bay, North Bay, and San Francisco Peninsula. The available discharge and suspended sediment load data were stratified for the three provinces, and this led to a significant improvement in correlation between the annual peak discharge and suspended load. To apply this method across the whole watershed, peak flow was estimated in ungauged areas using regressions from Rantz (1971).

This combined Napa/Alameda frequency distribution was applied to watersheds without flow records, and the resulting discharge estimates were combined with derived site-specific suspended sediment regression equations to estimate contemporary average suspended sediment loads for each watershed. For watersheds with sediment monitoring stations, watershed-specific sediment load regressions were developed.

Land-use-based method

In urbanized watersheds, the flow-based method described above cannot be applied due to a lack of sufficient data. Therefore, to estimate the loads contributed by very small lowland watersheds dominated by coastal marshes or urbanized and industrial land uses, a method based on land use-specific sediment yields was applied (Donigian & Love, 2003). A sediment delivery ratio was used to estimate the fraction of gross sediment erosion that reaches the channel ("edge of stream" inputs). The method employed was developed by USDA (NRCS, 1983):

$$DR = 0.417762 \times A^{-0.134958} - 0.127097 \tag{2}$$

where DR is the delivery ratio, which decreases as watershed size increases, and A is the watershed area (miles^2).

Due to the specific design and limitations of the numerical model developed here, the system in equilibrium conditions will be understood as watersheds that have adjusted all processes that control the supply of fluid and sediment to achieve constant sediment output rates. For a fluvial system, it seems reasonable to assume that equilibrium conditions are associated with each new equilibrium value of discharge. In other words, if discharge is sustained for a long enough period of time it will produce a new equilibrium width and sediment discharge (Rhoads, 1992). Californian rivers usually have narrow valleys and/or incised channels. During drier years deposited channel sediment is reworked and transported downstream. Therefore, we assume that over the long term, the same volume of sediment, which was delivered to a channel, is transported to the Bay. Such a simplification is not valid for shorter periods of time (for example decades or years). Suspended sediment load to the Bay for a given land use, in a given watershed, is the product of the sediment yield, the DR, and the area of the land use in the watershed.

Construction activities generate substantial amounts of sediment within a watershed and urbanizing specific sediment yields are about 100 times higher than erosion rates reported for older, reasonably stable urbanized areas, and about 250 times greater than most natural areas with low or no measurable human impact. In the Bay Area, intensive construction activities in recent years took place in the upland areas of the larger Bay Area watersheds. Therefore construction impacts on sediment loads already are included in the flow–sediment load type of correlation used for the large, mostly non-urban (but gradually urbanizing) watersheds.

RESULTS

Measured annual suspended sediment loads in Bay Area watersheds vary by orders of magnitude between years. Peak discharge variability is over three orders of magnitude, affecting load variability by four orders of magnitude. Large watersheds have low annual average rainfall; therefore, they have much greater inter-annual flow and suspended sediment load variability than smaller watersheds. Overall, a watershed's rainfall–runoff process is the primary determining variable for sediment transport.

Estimated average annual sediment loads varied considerably between watersheds due to size, flow characteristics, topography, geology, and land use. Given the influence of watershed size on annual average flow and suspended sediment load, the best way to compare one watershed directly to another is to normalize annual average loads by the area of the watershed. The estimated yield in Bay Area watersheds varied from 30 to 1100 t km^{-2}. The greatest yields tended to occur in smaller, steep watersheds. The largest sediment yields were associated with two watersheds that were undergoing urbanization (e.g. Colma Creek watershed yield = 1100 t/km^{2}; Zone 6 Line B watershed yield =13 000 t/km^{2}).

In the other class of watersheds, where urban land use dominates, and where the land use based suspended sediment yield method was applied, average annual suspended sediment yields were estimated to vary from 40 to 790 t km^{-2}. Regionally, the contemporary average annual sediment loads entering the Bay from local watersheds (an area of 8180 km^{2}) is estimated to be 1 300 000 t. This is equivalent to an average of 160 t km^{-2}. A comparison of the two methods of calculation showed similar regional results. Regionally, however, 35% of the load was estimated using the land use sediment yield-based method in an area totalling 2860 km^{2}. We now have evidence that 56% of the allochthonous suspended sediment load entering the Bay on average each year, is derived from local small tributaries draining to the Bay (Krone, 1979; Porterfield, 1980; McKee *et al.*, 2003).

CONCLUSION

In our study, we explore and evaluate hydrologic, physical, and land-use characteristics of San Francisco Bay watersheds to predict relationships between watershed sediment load and geomorphic processes, and ultimately provide an updated estimate of regional suspended sediment loads from small tributaries.

Among such physical variables as drainage area, peak annual discharge, land-use/ construction/development, geology, and topography, the best predictor of sediment load from the San Francisco Bay watersheds is peak discharge. This probably occurs because each year the long, dry summers return the systems to virtually the same condition by October (Krone, 1979). If this were not the case, multiple successive wet or dry years that commonly occur during the normal climate regime in the Bay Area would confound the correlation. Thus, higher volumes of sediment are eroded and transported during higher runoff and proportionally lower sediment erosion and transport during lower runoff. These observations are consistent with those of other authors (Dendy & Bolton, 1976; Syvitski & Milliman, 2007).

Watershed-specific sediment load is considered to be inversely related to drainage area (Vanoni, 2006). Available data illustrate that sediment loads have a weak correlation with drainage area (R^{2} = 0.66). The results improved, to some degree, when sites were sorted into distinctive geomorphic provinces. Topography is another factor that is generally correlated with sediment load, because steep slopes should result in high sediment loads. In the Bay Area, however, the steepest watersheds are, in many cases, associated with erosion-resistant lithologies. This complicates a possible sediment production correlation based only on slope. Bedrock resistance to erosion has a great impact on headwater and in-channel sediment production. It is possible that the impact of lithology in the Bay Area is overshadowed by tectonics, weathering, or vegetation.

In recent years there is growing evidence indicating that sediment loads may be dominated in some Bay Area locations by episodic events such as debris flows and wild fires (e.g. Kirchner, 2003). In our load to peak discharge statistical correlations, the sediment supplied by landslides and fire already is accounted for in the sediment statistics provided by the USGS gauges. At the Holocene time scale, these processes are responsible for an order of magnitude larger sediment input than all the other sources combined (Kirchner *et al.*, 2001).

Despite the significance of individual correlations with different physical variables, we are unable to generate a multiple regression model based on the available sediment data set. We do not suggest a lack of relationship between multiple variables and the sediment load. Rather we suggest that the available sediment record is spatially and temporally limited and strongly nonlinear; therefore it is difficult to detect statistically significant correlations between multiple variables in a variety of spatial and temporal settings. Sediment dynamics in a watershed are stochastic and the prediction of sediment load in any part a fluvial system comprises multiple assumptions, uncertainties, and errors. Our estimates when summed to the regional as a whole may be accurate within ±50%.

The estimate presented for San Francisco Bay sediment input, excluding the Delta, indicates that the long term average input into the Bay is higher than previously believed. The literature review completed by McKee *et al.* (2003) showed that previous estimates ranged between 320 000 and 1 000 000 metric t/year. The main reason why the estimates from the present study are greater than those of previous studies appears to be that our methods took into account the influence of watershed size on effective sediment load. This was achieved largely because of the availability of watershed boundary information in GIS format that was not previously available. The second significant reason was the availability of new data. In some cases, previous estimates have been biased low because of the use of dry weather data (e.g. Davis *et al.*, 2000).

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