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Watershed Specific and Regional Scale Suspended Sediment Load Estimates for Bay Area Small Tributaries

Prepared by
Mikolaj Lewicki and Lester McKee
San Francisco Estuary Institute, Oakland, CA

December 2009

CONTRIBUTION
NO. 566
DECEMBER
2009

SAN FRANCISCO ESTUARY INSTITUTE
7770 Pardee Lane, Second floor, Oakland, CA 94621
p: 510-746-7334 (SFEI), f: 510-746-7300, www.sfei.org

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Mikolaj Lewicki and Lester McKee
San Francisco Estuary Institute

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This report can be cited as:

Lewicki, M., and McKee, L., 2009. Watershed specific and regional scale suspended sediment loads for Bay Area small tributaries. A technical report for the Sources Pathways and Loading Workgroup of the Regional Monitoring Program for Water Quality: SFEI Contribution #566. San Francisco Estuary Institute, Oakland, CA. 56pp.

EXECUTIVE SUMMARY

Since it has been recently confirmed that the suspended sediment load entering the Bay from the Central Valley via the Delta is decreasing over time, it is reasonable to suspect that loads from small local tributaries may constitute an increasing component of the overall Bay sediment budget. However, because previous estimates of suspended sediment loads entering San Francisco Bay from local tributaries are likely outdated because of evolving land uses around the Bay and because new methods of analysis are now available, it is difficult to conclude with confidence the magnitude and relationships between each component of the sediment budget. Given the importance of suspended sediment in management strategies for many surface-reactive pollutants (e.g. certain trace metals and hydrophobic organic pollutants) and the likelihood that previous estimates are not representative of the present day, this report presents updated estimates of suspended sediment loads entering San Francisco Bay from local tributaries in the nine-county Bay Area.

Local discharge and suspended sediment data collected by the United States Geological Survey and its collaborators were compiled for 29 watersheds in the vicinity of the Bay Area spanning Water Years 1957 to 2007 (a total of 177 station years). These data we analyzed statistically to determine if factors that are known to influence sediment loads could explain some of the variability in loads between watersheds. The tested watershed characteristics (independent variables) included: drainage area, watershed slope, hydrology, climate, geology/soils, and land use. Based on this analysis it was found that peak flow explained most of the variability and that land use (our interest was in urban land use) did not explain sufficient variability to allow for the extrapolation of measured sediment load data to watersheds dominated by urban land use. Therefore, three methods were used to estimate sediment loads for the region: 1. Where data existed for a specific watershed, this data was used and interpolated climatically using its own watershed specific regression equation), 2. For watersheds dominated by non-urban land use where no USGS data has been collected, a regional regression relationship was applied specific to three sub-regions (Peninsula, North Bay, East Bay), and 3. For watersheds dominated by urban land use (and some small non-urban near Bay watersheds), a land-use based estimation method was applied based on data extracted from published literature on land use specific sediment yields.

Measured annual suspended sediment loads in Bay Area watersheds vary inter-annually by two to four orders of magnitude. For example, USGS-measured annual suspended sediment loads in Alameda Creek at Niles, with 22 years of record, have varied between 9 and 766,493 metric t (a variation of over 85,000 times between years). Annual average sediment loads vary considerably between watersheds due to watershed size, flow characteristics, and land use. Predicted long term average load in watersheds where the USGS has made measurements varied from 31- 1,130 t/km^2. For urban watersheds near the Bay margin, annual average suspended sediment yield was estimated to vary from 44-788 t/km^2. These yields were estimated assuming the watersheds were not undergoing significant land use change and therefore the loads being produced are relatively stable. Colma Creek in South San Francisco and Zone 6 Line B at Warm Springs Boulevard in Fremont are examples in the Bay area where USGS measurements have been conducted in watersheds that were rapidly urbanizing. The average annual yield for Colma Creek was 1,136 t/km^2 for the period 1966 - 1977. The yield for Zone 6 Line B was 13,493 t/km^2 for the period WY 2000 - 2002.

Regionally, the new discharge- and land-use-based estimate of contemporary annual average suspended sediment loads entering the Bay from local Bay Area watersheds in the nine-county

Bay Area (an area of 8,180 km^2) is estimated to be 1,269,600 metric t. This is equivalent to an average of 155 metric t /km^2. It is estimated that 35% of this load is associated with mostly urbanized watersheds near the Bay margin comprising 2,870 km^2. Our updated estimate is one of the first to distinguish between the sediment contributions from urbanized and non-urbanized areas, which is a critical distinction for many pollutant control strategies. If these loads are summed for RMP Bay segments, we estimate that annual average suspended sediment loads from local small tributaries range between 214,900 and 270,200 metric t for the most urbanized Bay segments (Central Bay, South Bay and Lower South Bay). Immediate uses of this new information include providing basic input data for 1. Prioritizing watersheds for study, 2. Making new estimates of regional scale contaminant loads, 3. Models that describe and predict the fate of pollutants, 4. Decisions about dredging waterways, and 5. Decisions about wetland restoration.

ACKNOWLEDGEMENTS

Most of the data reviewed and analyzed in this report was gathered over the past 50 years by the USGS and its local funding and cooperating partners. USGS data on geology, topography, water flow, and suspended sediment concentrations and loads were downloaded from the World Wide Web using various USGS data download tools. Precipitation data were obtained from NOAA and land use data from ABAG.

We would like to also acknowledge a partnership between William Lettis and Associates, Oakland Museum of California, SFEI, and local cities and counties who provided both in-kind effort and funding that generated watershed boundary data for urban areas on the Bay margin. This is a 15 year effort and while much has been achieved, there still remains a data gap in southern Marin, Vallejo, and along the urban corridor between Pinole and Pittsburg. The specificity of the sediment load estimates provided in this report could not have been achieved without urban watershed boundary mapping.

We acknowledge the Sources Pathways and Loadings Workgroup (SPLWG) of the Regional Monitoring Program for Water Quality (RMP) in all project stages from concept development through to review of the final draft. We would like to especially acknowledge all the RMP program participants. Lastly we are thankful for the review comments from Dr. David Schoellhamer, USGS, Sacramento, Dr. James Kuwabara. USGS, Menlo Park, Dr. Barbara Mahler, USGS, Austin, Texas, Dr. Khalil Abusaba (Brown and Caldwell on behalf of BASMAA and the Contra Costa Clean Water Program), Mr. Chris Somers (BASMAA and EOA), Ms Nicole David, SFEI, and Ms Carrie Austin, Region 2 Water Board (RWQCB) that helped greatly to improve the report and make it more useful for aiding future management of the Bay.

Funding ($40,000) for the project was provided by the Regional Monitoring Program for Water Quality.

TABLE OF CONTENTS

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, recreation amenities, native species habitat, and disruption of commercial shipping operations. The San Francisco Bay aquatic ecosystem is an example of a system that has deteriorated over the past century and a half in response to the pressures of human population growth, reclamation of wetlands on the Bay margin, resource extraction, and agriculture.

In San Francisco Bay, accurate information about sediment loads is critical to at least four specific management areas:

1) Sediments can be pollutants in themselves, degrading riparian habitat through siltation,
2) Sediments carry particle-associated pollutants, such as mercury, PCBs, and legacy organochlorine pesticides. Regional strategies to abate these pollutants, including Total Maximum Daily Loads (TMDLs) direct many implementation actions towards identifying and abating sources of contaminated sediments, with the goal of accelerating the long term decrease in the pollutant concentration of Bay sediments. For some pollutants (e.g., PCBs), it has been demonstrated that sediments originating in urbanized areas are more contaminated compared to sediments originating in non-urbanized areas (Kinnetic Laboratories Incorporated, 2002),
3) Sediment is dredged annually from shipping channels. Understanding the sources of sediments in specific areas of the Bay could assist authorities to plan resources and focus attention on management measures,
4) Sediment budgets in different segments of the Bay are critical for predicting the accretion rate in restored tidal wetlands that are created by breaching levees that separate former salt producing ponds and agricultural lands from the Bay.

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.

San Francisco Bay has been described as the most impacted urban estuary on the West Coast. Between 1849 and 1970, over 40,000,000 kg of mercury were extracted from more than a dozen mining areas within the nine-county Bay Area, most of which was extracted during the gold rush from the New Almaden Mines in the Guadalupe River watershed (South San Francisco Bay) and transported to the Sierra Nevada Mountain Range (eastern California) for gold processing (Cargill et al., 1980; Hylander and Meili, 2003; Alpers et al., 2005). Following the gold rush (1849-1880), human population increased rapidly (ABAG, 2008) as gold workers created a new life in the Bay Area. Between 1850-1940 much of the forested land of the Bay Area was cleared of high grade timber trees to build the three largest and oldest cities (Oakland, San Francisco, and San Jose), and to make way for agriculture. Today more than 13 million people reside in the Golden Gate watershed (which includes 37% of the area of California) and over seven million live in the conurbation of the nine-county Bay Area. Today about 35% of the Bay Area is urbanized and about 15% is actively managed farmland, with the remainder classified as open space (although much of this is managed "rangeland" for cattle grazing). These major waves of land use change have led to wholesale, but time-dependant, changes in the supply of sediment to San Francisco Bay.

Conceptually, we assume that there was a large increase in sediment loads entering the Bay from local small tributaries during the last quarter of the 19th century due to mining and timber-getting and perhaps another peak post WWII due to urban and industrial development. These increased loads are documented in some watersheds (i.e., amount of dredging in the Petaluma River) (PWEP, 1999). However, in other watersheds these processes do not match up temporally with the evidence of sedimentation changes in the Bay (Foxgrover et al., 2004; Jaffe and Foxgrover, 2006). It is possible that sedimentation in the large Bay Area watersheds peaked prior to the 1940s, or lagged several decades behind each wave of anthropogenic disturbance due to temporary storage of sediment within watersheds (McKee et al., 2003).

Estimates of suspended sediment loads entering San Francisco Bay from local tributaries in the nine-county Bay Area have been presented by a number of researchers (e.g., Gilbert, 1917; Krone, 1979; Russell et al., 1980; Porterfield, 1980; Goodwin and Denton, 1991; Ogden Beeman and Associates, Inc., 1992; Abu Saba and Tang, 2000; Kondolf, 2000; Davis et al., 2000; McKee et al., 2003). Each author chose from the variety of available methods of quantification, for example, total basin deposition (Gilbert, 1917) or various sediment rating curve methods using either daily or annual discharge (Krone, 1979; Porterfield, 1980; Goodwin and Denton, 1991; Ogden Beeman & Associates, 1992; Kondolf, 2000; Wright and Schoellhamer, 2004). Davis et al. (2000) used the SIMPLE model to estimate annual average discharge based on annual average rainfall and land use specific runoff coefficients. Discharge was then combined with land use specific estimates of suspended sediment concentration to derive load estimates. McKee et al. (2003) collated all existing suspended sediment concentration data collected by the USGS and its partners prior to and including the year 2000. These data were flow-weighted and combined with discharge records to estimate long term average loads for each location. Loads were then scaled up by the proportion of ungaged areas to estimate regional long term average load to the Bay.

Without exception, previous authors had to make some gross simplifying assumptions (usually by their own admission) in order to make regional scale suspended sediment load estimates. These simplifications included: combining watershed areas rather than using individual watersheds, using annual average hydrology, assuming the existing sediment data were representative of all watersheds in the Bay Area, and assuming that land use was homogeneous or had no impact on sediment loads. In particular, with the exception of Davis et al. (2000), previous authors did not distinguish between urban and non-urban land use. Many of these assumptions likely render the previous sediment loads estimates biased low. In addition, these estimates may be considered outdated because of the wealth of new data collected by the United States Geological Survey and local partner agencies at 11 locations from 2000-2007: a total of 37 additional water years of data.

Some of these reports provided an argument that suspended sediment loads entering the Bay from the Central Valley via the Delta are expected to decrease over time (Krone, 1979; Porterfield, 1980; Ogden Beeman & Associates, 1992; Wright and Schoellhamer, 2004). Thus loads from small local tributaries may be increasing in importance in relation to the suspended sediment delivered from the Central Valley (McKee et al., 2006). Currently it is suggested that approximately 40% of the total suspended sediment load entering the Bay may be contributed by urbanized and urbanizing areas from the small tributaries draining the nine Bay Area counties, an area less than five percent of the Bay's total watershed area upstream from the Golden Gate (McKee et al., 2006). The estimate of 40% was based on new estimates of reduced sediment load entering the Bay from the Central Valley (McKee et al., 2006), but relied on older information about the local tributary sediment load.

Given the importance of suspended sediment supply to the Bay outlined briefly above and the likelihood that previous estimates are not representative of the present day, the objective here was to develop a new statistical analysis of suspended sediment loads and to describe the methods used to derive new watershed-specific and regional estimates of current annual average suspended sediment loads. This new analysis is made possible by two important developments in the past five years:

1. Ongoing and recent local-agency-sponsored United State Geological Survey efforts to measure suspended sediment loads in Bay Area tributaries have increased the locally available data set substantially. McKee et al. (2003) only included years prior to water year 2000 data in their analysis and other previous authors were even more restricted.
2. Ongoing and recent local-agency-sponsored watershed mapping completed by the Oakland Museum of California and William Lettis and Associates. McKee et al (2003) did not have a completed map of urban drainage areas as a basis for watershed-specific suspended sediment load estimates.

In this contribution, the focus is the estimation of fine suspended sediment loads (about 80% of which is <0.0625 mm; silt and clay sized fractions) for the recent period. Bed load will not be discussed here mainly because of the lack of importance in the transport of hydrophobic pollutants. But bed load may represent the dominate sediment transport process for larger grain sizes with generally smaller surface-to-volume ratios than silts and clays that are present in the estuary. Immediate uses of this new suspended sediment information include improving the Bay sediment budget (Schoellhamer et. al 2007), providing basic input data for making new and improved estimates of contaminant loads to San Francisco Bay, input data to models that describe and predict the fate of Hg and PCBs (e.g. Oram et al., 2008; Oram et al., in preparation), and providing improved estimates of sediment loads in relation to dredging waterways and wetland restoration.

METHODS

For most regional watershed management planning purposes, annual- or decadal-scale estimates of channel suspended sediment loads are ideal. Here we estimate, using statistical methods, watershed-specific sediment inputs into San Francisco Bay from the watersheds of the nine-county Bay Area that drain to the Bay (8,180 km^2)[1]. 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 stream flow are critical components of determining suspended sediment load. Our study was based on the stream flow and sediment discharge characteristics of 29 gaged watersheds ranging in size from 2.0 km^2 to 1,639 km^2, located within the nine counties. Without double counting nested gages in a single watershed, these 29 gages together drain an area of 4,237 km^2 or about 52% of the area of interest. The Bay Area climate is Mediterranean with 95% of the precipitation taking place during the winter months (October to April). The annual precipitation in the study area varies from 300 mm near the Bay margin at sea level to more than 1500 mm on the highest mountains of the coast range. Some of the gaged watersheds in the Bay Area have one or more dams or other water retention structures that together are downstream from drainage areas totaling 1,600 km^2. The majority of this impoundment is located in the Alameda Creek, Coyote Creek, Guadalupe River, and Napa River drainages, all of which have been or are currently gaged for water and suspended sediment discharge. In general, downstream sections of watersheds adjacent to the Bay are highly urbanized while natural (open space) and agricultural land use types mostly are in upstream sections of the Bay watersheds.

Historically, estimates of the loads entering the Bay have focused on identifying statistically important relationships between watershed characteristics or physical processes and the annual suspended sediment loads specific for a watershed. At the scale and scope of the present investigation it was impossible to investigate detailed historical loads. Like previous authors of sediment load estimates in the Bay Area, we assume steady state (no trend in the discharge and suspended sediment data sets) for the period of data collection in the non-urban area (1957-2007), reasonable if we assume the greatest forcing factors are landscape erodability (geology, soils, climate, tectonic activity associated with the San Andreas fault zone) and agricultural land use. There is no conclusive research on the effects of climate change on Bay Area rainfall. We therefore assumed that current and future climate conditions will be similar to those of the past 50 years, although research contributions in the near future likely will call into question these steady-state assumptions.

In recent years, a variety of different methods have been developed and applied worldwide to estimate sediment loads from ungaged watersheds of varying size and land use and over a range of time periods. The most commonly applied techniques include predicting sediment loads as a function of different basin parameters such as area (Waythomas and Williams, 1988) or land use (Wollman, 1967). Methods also have been developed that use multi-metric basin land use and physical characteristics (geology,

[1] 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.

climate/precipitation, relief, drainage area) as sediment load predictors (Syvitski and Morehead, 1999; Syvitsky and Milliman, 2007). Another common technique is the use of rating curves based on flow duration coupled with sediment concentration or sediment load (Anderson, 1980; Porterfield, 1980). Heavy metal geochronologies, radionuclides, sediment traps, river morphologic surveys, and total basin deposition have also been applied to estimate average long-term sediment loads when time continuous gaging is lacking (Gilbert, 1917; Duck and McManus, 1994; Morris and Fan, 1997; Takahashi and Nakagawa, 1997). Cosmogenic studies usually are applied to estimate erosion rates over medium to very long periods of time (i.e., 10-10 000 years) (Walling et al., 1999, Granger and Mizikar, 2001; Kirchner et al., 2001). In more recent years, a number of numerical models have been applied to estimate sediment loads from ungaged basins. Hydrological Simulation Program - FORTRAN (HSPF) and FLOWSED Model are comprehensive packages for simulation of watershed hydrology and sediment loads. These numerical models essentially package a selection of the methods described above into a single integrated computational tool. A user calibrates the model, using site-specific settings, by defining the temporal and spatial magnitude of various independent variables and physical parameters. The reported suspended sediment loads, in most cases, have been generated using empirical observations and/or one or a combination of these methods.

The applicability of each method to a specific watershed or management question is influenced by available data and expertise, basin size or the number of sub-basins requiring discrete information, and the desired temporal resolution. For example, the application of area as a proxy for sediment load is restricted by the scale of a basin (Waythomas and Williams, 1988). Describing sediment load as a function of the drainage area may be misleading and consequently may lead to inaccurate results especially as basin scale increases or if multiple watersheds have lithologies that differ. Foster et al. (1990) recognized that short-term hydro-sedimentological processes must be monitored by direct measurements, whereas medium-term processes may be characterized by reservoir surveys and long-term processes by palaeo-hydrological investigation.

The local discharge and suspended sediment data collected by the United States Geological Survey and its collaborators were compiled for 29 watersheds in the vicinity of the Bay Area spanning Water Years 1957 to 2007 for a total of 177 station years (Tables 1). These data were downloaded using the USGS website web query tool (e.g., USGS 2007). Spatial characteristics (that have been identified in California and other parts of the world as independent variables for the prediction of sediment loads) were compiled for the Bay watersheds using local, state, and federal government data sources and ESRI (GIS) software. The tested watershed characteristics (independent variables) included: drainage area (derived from the 30-m USGS digital elevation model (DEM)), watershed slope (calculated within the GIS from the DEM), hydrology (represented by flow parameters such as daily discharge and peak discharge derived from USGS gaging station data), climate data from the National Oceanographic and Atmospheric

Table 1. USGS flow and suspended sediment loads data used in this analysis.

Location Name	Gage number	Flow data	Suspended sediment data

East Bay			
Alameda Ck. At Niles	11179000	1956-2007	1957-1973, 2000-2007
Arroyo De La Laguna at Verona	11177000	1970-1983, 1988-2003	2000-2003, 2007
Alameda Ck. Below Welch Ck. Near Sunol	11173575	2000-2006	2000-2003, 2007
Arroyo Valle Near Livermore	11176500	1960-2007	1963, 1965-1967
Arroyo Valle Below Lang Canyon Near Livermore	11176400	1964-2007	1974-1977, 1979
Cull Ck. Above Cull Ck. Reservoir Near Castro Valley	11180960	1979-2006	1979-1989,1992, 1995-2006
Cull Ck. Below Cull Creek Dam Near Castro Valley	11180965	1979	1979
San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley	11180825	1981-1991, 1993-1994, 1998-2006	1981-1989,19921994, 1998-2006
Crow Creek Near Hayward	11180900	1998-2006	2000-2003
San Lorenzo Ck. At San Lorenzo	11181040	1969-1997	1992
Zone 6 Line B At Warm Springs Boulevard At Fremont	11172365	2000-2002	2000-2003
Coyote Ck. Above Highway 237 At Milpitas	11172175	1999-2007	2004-2007
Coyote Ck. Near Gilroy	11169800	1961-1982	1961-1975
Walnut Ck. At Concord	11183600	1969-1992	1966-1971
Wildcat Ck. At Vale Road At Richmond	11181390	1976-1997	1978-1980
Peninsula			
Guadalupe R. At San Jose	11169025	2003-2006	2003-2006
San Francisquito Ck. At Stanford	11164500	1960-2007	1962-1970, 1974
Colma Ck. At South San Francisco	11162720	1964-1994, 1996	1966-1976
Permanente Ck. Near Monte Vista	11166575	1985-1987	1985-1987
West Fork Permanente Ck. Near Monte Vista	11166578	1985-1986	1986
Pescadero Ck. Near Pescadero	11162500	1960-2007	1980
San Gregorio Ck. At San Gregorio	11162570	1970-2005	
North Bay			
Sonoma Creek At Agua Caliente	11458500	1961-1981, 2002-2006	
Sonoma Creek At Boyes hot spring	11458500	1956-1962	1956-1962
Pine Ck. At Bolinas	11460170	1968-1970	1968-70
Corte Madera Ck. Near Ross	11460000	1960-1993	1978-1980, 1984
Napa R. Near Napa	11458000	1960-2006	1977-1978
Napa River Near Saint Helena	11456000	1960-1996, 2001-2006	1962
Lagunitas Ck. At Samuel P. Taylor State Park	11460400	1983-2007	2004-2006
Walker Ck. Near Marshall	11460750	1983-2006	2004-2006

Administration (NOAA), geology/soils (USGS and United State Department of Agriculture (USDA); represented by the erodibility factor), and land use (Associations of Bay Area Governments (ABAG)). We tested whether estimations of the sediment loads entering the Bay could be improved based on availability of the new local data.

Regression analyses were performed between the individual spatial parameters and measured suspended sediment loads to test the ability of individual parameters to explain the variation in the dependent variable (suspended sediment load). The coefficient of determination (R^2) was used for this test (Table 2). In this analysis, urban land use explained little of the variation in sediment loads in Bay Area watersheds monitored to-date. This is because urban land use was not sufficiently sampled in the different Bay Area 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 the Bay Area watersheds into watersheds of mainly non-urban land use and mainly urban land use and apply a specific sediment load estimation method to each class. Such stratification was a weakness in much previous estimation (e.g. Krone, 1979; Porterfield, 1980; Ogden Beeman and Associates, Inc., 1992; McKee et al., 2003). These authors scaled sediment loads by area assuming no variation in yields between land uses and assuming that data collected by the USGS in watersheds dominated by agriculture and open space are representative of all Bay Area landscapes.

FLOW-BASED METHOD

Estimation of the suspended sediment loads leaving watersheds of mostly non-urban land use were estimated by applying local empirical statistical relationships relating sediment loads to physical characteristics of gaged watersheds. This appears valid for the San Francisco Bay watersheds because suspended loads are less than the theoretical transport capacity (Porterfield, 1972; Walling, 1977). In the San Francisco Bay watershed, most of the gaging stations monitor watersheds dominated by natural (open space) and or agricultural land use. The local rivers are highly event driven and produce the majority of long-term flow and sediment discharge during short-lasting, intense winter storms occurring mostly in December-March (Kroll, 1975; McKee et al., 2003). On average, half of the annual discharge and ~ 90% of the sediment load occur during just a few days per year (Kroll, 1975, Warrick and Milliman, 2003; McKee et al., 2003). We found that for the non-urban watersheds, annual peak discharge correlated with annual sediment load better than did annual total flow or any other independent variable we tested (Table 2). This is perhaps not surprising since USGS sampling programs have applied the techniques of Porterfield (1972) for the construction of sediment rating curves. Following the Porterfield method, suspended sediment discharge is computed by the USGS as the product of flow and the flow-dependent sediment concentration. That is, the daily (summed to wet season) suspended sediment load data used here is already computed from flow (rating curve) based on USGS field measured instantaneous data (for a number of storms each year rather than measured. While it could be argued that the USGS records have limited accuracy, when comparing one watershed to another large explainable differences in yields appear logical.

Table 2. Drainage area, peak discharge and geology correlations with sediment load.

Sub-region	R^2	Intercept	Slope	p
Drainage area				
Peninsula	0.44	0.662	1142.9	0.104
North Bay	0.85	0.677	1053.6	<0.0001
East Bay	0.20	0.167	10043	0.009
Entire Bay	0.38	0.389	3576.7	0.004
Peak discharge				
Peninsula	0.62	1.911	0.261	0.003
North Bay	0.71	2.098	0.042	0.005
East Bay	0.94	1.498	2.567	<0.0001
Entire Bay	0.86	1.444	2.108	<0.0001
Peak discharge & geology				
Weak Geology	0.85	1.43	2.56	<0.0001
Average Geology	0.46	1.63	0.87	0.114
Resistant Geology	0.69	1.34	1.1	<0.0001
Peak discharge & slope				
Slope (0-3 percent)	0.66	0.06	4.38	0.027
Slope (3-20 percent)	0.88	*3.08*	1.46	<0.0001
Slope (>20 percent)	0.67	1.72	1.08	0.351
Peak discharge & land use (Alameda County)				
Natural	0.89	0.51	1.75	<0.0001
Urban	0.91	3.25	1.51	<0.0001
Combined Natural and Urban	0.95	1.498	2.567	<0.0001

Peak discharge is related to sediment load using a power function (Leopold and Wolman, 1956; Muller and Forstner, 1968):

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

where Q_s represents sediment load, Q_p represents peak discharge, 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 (units volume per unit time) to suspended sediment loads (units mass per unit time)). These parameters are also dependent on land use, climate, and hydraulics and are also dependant on particle size distribution (as mentioned earlier about 80% of particles are in the silt and clay fractions).

Rantz (1971) identified three distinct hydrogeomorphic provinces in the Bay Area largely defined by climate and geology. For this study, we divided the Bay watershed into the same three geomorphic provinces as Rantz: East Bay (Contra Costa and Alameda Counties), North Bay (Marin, Sonoma, Napa, and Solano Counties), and San Francisco

Peninsula (South San Francisco, San Mateo, and Santa Clara Counties). We stratified the available discharge and suspended sediment loads data (Table 1) for the three provinces and found 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 ungaged areas using regressions from Rantz (1971):

$$Q_1 = 0.33Q_2 \quad (2)$$
$$Q_2 = 0.069A^{0.913}P^{1.965} \quad (3)$$
$$Q_5 = 2.00A^{0.925}P^{1.206} \quad (4)$$
$$Q_{10} = 7.38A^{0.922}P^{0.928} \quad (5)$$
$$Q_{25} = 16.5A^{0.912}P^{0.797} \quad (6)$$
$$Q_{50} = 69.6A^{0.847}P^{0.511} \quad (7)$$

where Q represents 1-, 2-, 5-, 10-, 25-, 50-year peak discharge (cfs), A represents drainage area (miles^2), and P represents a watershed average precipitation (inches) extracted from the GIS isohyets layer. The frequency of 1-, 2-, 5-, 10-, 25-, and 50-year peak discharges during the last 50 years was estimated for ungaged watersheds based on the record of Napa and Alameda USGS gages. If a watershed had a flow monitoring station the local data was applied. Otherwise, the number of 1-, 2-, 5-, 10-, 25-, and 50-year events during the last 50 years was counted.

This combined Napa/Alameda frequency distribution was applied to watersheds without flow record and the resulting discharge estimates were combined with the locally derived suspended sediment regression equations to estimate contemporary average suspended sediment loads for each watershed. For watersheds with sediment monitoring stations, watershed-specific sediment loads regressions were developed (Table 3). If a monitored watershed had four or less years of record, its regression rating curve was derived by merging its record with a neighboring monitored watershed of a similar size. For example, this was done for Corte Madera Creek near Ross using data from Pine Creek. Pine Creek at Bolinas does not flow into the Bay but drains Mt Tamalpais and shares the similar watersheds characteristics to Corte Madera Creek near Ross.

Table 3. Peak discharge correlated with sediment load measured by USGS.

Watershed	R^2	Intercept	Slope	n	Dates
San Francisquito Ck.	0.81	2.42	0.02	8	1962-70
Alameda Ck.	0.91	1.72	2.42	39	1957-73, 2000-07
Coyote Ck.	0.97	2.52	0.02	15	1962-76
Sonoma Ck.	0.66	1.75	0.14	7	1956-1962
Corte Madera Ck. & Pine Ck.	0.84	2.47	0.009	6	1968-70, 1978-80
Colma Ck.	0.35	1.65	0.81	11	1966-76

LAND USE BASED METHOD

In the lowland urbanized Bay watersheds (Figure 1) the pattern of land use modifications was coupled with reduced or no sampling effort of sediment loads. Only 14 years of the total 177 station years of USGS data record were collected by the USGS in just two watersheds of the Bay Area that were urbanizing during the period when data were collected (Colma Creek and Zone 6 Line B). The flow-based method described above cannot be applied to urbanized/urbanizing areas, due to lack of sufficient data, without risking bias in the estimate. Therefore, to estimate the sediments loads contributed by lowland non-urban or urbanized and industrial land use in the Bay Area, a land-use based estimation method was applied based on data extracted from published literature on land use specific sediment yields similar to the methods of Donigian and Love (2003). This commonly accepted approach is part of integrated flow and sediment prediction models such as Hydrologic Simulation Program-Fortran (HSPF) (EPA, 2008). Typical ranges of expected erosion rates from Donigian and Love (2003) and the HSPF manual were applied to the urbanized watersheds extracted from our GIS database (Table 4). A sediment delivery ratio was used to estimate the fraction of gross sediment erosion occurring in a land-use segment that reaches the channel (“edge of stream” inputs). We used the method developed by USDA (NRCS, 1983):

$$DR=0.417762*A^{-0.134958}-0.127097 \qquad (8)$$

where DR is the delivery ratio (decimal fraction), which decreases as watershed size increases, and A is the watershed area (miles^2). We further assume that all sediment delivered to a channel is transported to the Bay. Suspended sediment load to the Bay for a given land use in a given watershed is the product of the sediment yield from Table 4, DR, and the area of the land use in the watershed.

Table 4. Sediment production rates estimated for selected land use type classes (metric t/km^2/year) (regional erosion rate).

Natural	Agriculture	Low Density Urban	High Density Urban	Industrial
72	2,461	450	996	1,836

Construction activities generate substantial amounts of sediment within a watershed (especially if the terrain is steep). Uncontrolled erosion from construction activities in urbanizing areas can generate 5,000 – 50,000 metric t/km^2/year (Leopold, 1968; also see recent thorough review by Chin, 2006). In comparison, typical erosion rates for cropland are approximately 50 metric t/km^2/year (Dreher and Price, 1992) (edge of stream estimations). This urbanizing sediment yield rate is 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,

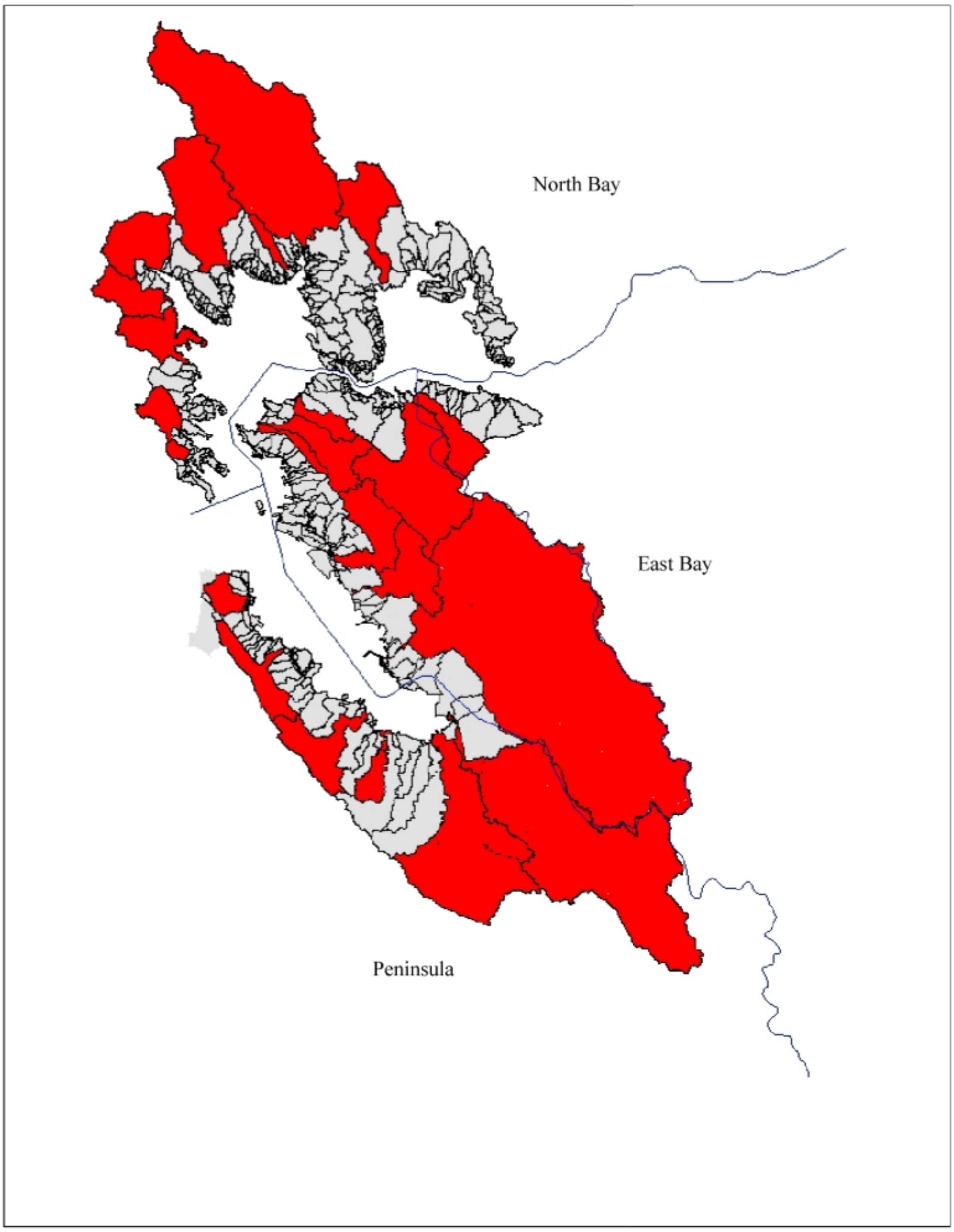

Figure 1. Map showing the classification of watersheds for computations. In the watershed areas shaded in the red color, either a watershed specific regression or a regional regression (specific to the North Bay, East Bay or Peninsula) was used to calculate annual average loads. These regressions or rating curves as they are sometime called were based on USGS measurements of peak discharge and annual wet season suspended sediment loads. In the areas shaded in grey, a land-use yield method was used based on data extracted from published literature similar to the methods of Donigian and Love (2003).

examples of low yielding watersheds include Alameda Creek, Coyote Creek and Guadalupe River (additionally, in these watersheds a fraction of the load was removed by the reservoirs). However, intensive construction activities in the recent years took place in the upland areas of larger Bay Area watersheds. Therefore construction impacts to sediment loads are already included in the flow-sediment load type of correlation used for the large mostly non-urban (but gradually urbanizing) watersheds.

DATA ANALYSIS

We used all historic and current gaging station suspended sediment and flow records (Table 1; Appendix 1 and 2) to determine sediment loads in relation to watershed size, location, and discharge. McKee et al. (2003) compiled a suspended sediment database of all USGS data up to water year (WY) 2000 – it was this database that was updated. For watersheds with reservoirs, the area above the reservoirs was not clipped out of the overall watershed area. There is some evidence that reservoirs in the Bay Area trap suspended sediment not just bed load. For example, Cull Creek reservoir trapped about 95% of its suspended sediment supply during the dry year of WY 1979. But evidence is lacking for wet years when the flushing time for reservoirs would be much shorter.

So in this analysis we assume that the design of the Bay Area reservoirs allows the suspended sediment to bypass with only limited deposition certainly during wetter than average years and perhaps at other times as well. We make this assumption for three reasons. First, USGS measurements show that 80% of suspended sediments in Bay Area drainage lines are <63 microns in size, 65% are < 20 microns and 55% are < 10 microns (McKee unpublished information). These observations are probably related to the clay loam soils found here. The settling time for such small particles is long (between 5 cm per hour (10 microns assuming a particle density of 1.5 g/cm^3) and 40 cm per hour (20 micron particles at 1.5 g/cm^2). Second, mean annual loads are bias towards wet years. For example in Alameda Creek, we estimate that the 7 wettest years on the last 51 carried the same load as the driest 44 years, or that 14% of the years account for 52% of the suspended sediment load. Finally, the large reservoirs in the Bay Area are on the Napa River, San Lorenzo Creek, Alameda Creek, Coyote Creek, Guadalupe River, and San Francisquito Creek. These watersheds have sediment gaging programs. Therefore reservoir operations and any trapping already are included in our calculations.

The topography and slope values for each sub watershed were calculated from the 10m DEMs, and the resulting slope grids were re-classified into three groups: 0-3 percent slope, 3-20 percent slope, and greater than 20 percent slope. The fraction of the total watershed area within each of these groups was computed. The mean annual precipitation was extracted from the GIS-based map digitized by SFEI staff and based on the data from Rantz (1971) and clipped to each watershed. The Bay Area land-use coverage provided by ABAG was generalized into five main land-use categories and clipped to each watershed. Based on experience gained from detailed geomorphic study in seven watersheds and a number of reconnaissance studies in all nine counties of the Bay Area, an understanding of the spatial variability of erosion in relation to lithology has been developed (Pearce et al., 2002; 2003a; 2003b; 2004; 2005; 2006; 2007; Brady et al., 2004; Grossinger et al., 2006; Bigelow et al., 2008). This knowledge base was used to classify each watershed in the Bay Area into five discrete erosional categories based upon the dominant lithologies in each watershed (Sarah Peace, SFEI unpublished data). This approach was all that was available for generalization of the bedrock characteristics within each basin as there is no published literature on erosion characteristics of Bay Area lithologies.

In our analysis, annual sediment loads were related to stream discharge and other parameters by a power relation. For each statistical relation, we report regression equations including the intercept and slope of the power trend lines, as well as the coefficients of determination, R^2 (Table 2). Our analysis identifies the annual peak flow (either measured or simulated using regressions from Rantz (1971)) as having the most statistically significant correlation with the suspended sediment loads. The results show substantial improvement in correlation between the annual peak discharge and suspended load if sites are stratified into distinct geomorphic provinces of the San Francisco Bay (Figure 2). The correlation coefficients (R^2) were 0.62 for the Peninsula, 0.71 for the North Bay, and 0.94 for the East Bay. In case of the North Bay and East Bay the low flow outlier points were not used in the correlation.

RESULTS

Measured annual suspended sediment loads in Bay Area watersheds vary by orders of magnitude between years (Appendix 2A, B, C). Three watersheds that have long records of measured suspended sediment exemplify this. Twenty-five years of USGS measured suspended sediment loads in Alameda Creek at Niles (USGS gage number 11179000) show a variation between 766,493 metric t recorded in 1958 to just 9 metric t recorded three years later in 1961 (a variation of over 85,000 times between these two years). In Cull Creek above Cull Creek Reservoir near Castro Valley (11180960), the USGS recorded suspended sediment loads have ranged between 98 and 93,217 metric t (a variation of 950 times). In San Lorenzo Creek above Don Castro Reservoir near Castro Valley (11180825), recorded sediment loads have ranged between 279 and 151,514 metric t (a variation of 540 times). Peak discharge variability is over three orders of magnitude affecting load variability by four orders of magnitude (Figure 3). Bay Area watersheds that are large and have low annual average rainfall, like Alameda Creek, have much greater inter-annual flow variability and much greater suspended sediment load variability than Bay Area watersheds with smaller watershed area. Overall, however, this graphical relation suggests that for Bay Area watersheds the rainfall runoff process is the primary determining variable for sediment transport.

Estimated annual average sediment loads varied considerably between watersheds due to size, flow characteristics, topography, geology, and land use (Table 5). 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 (called yield or unit export ($t/km^2/yr$)). The estimated

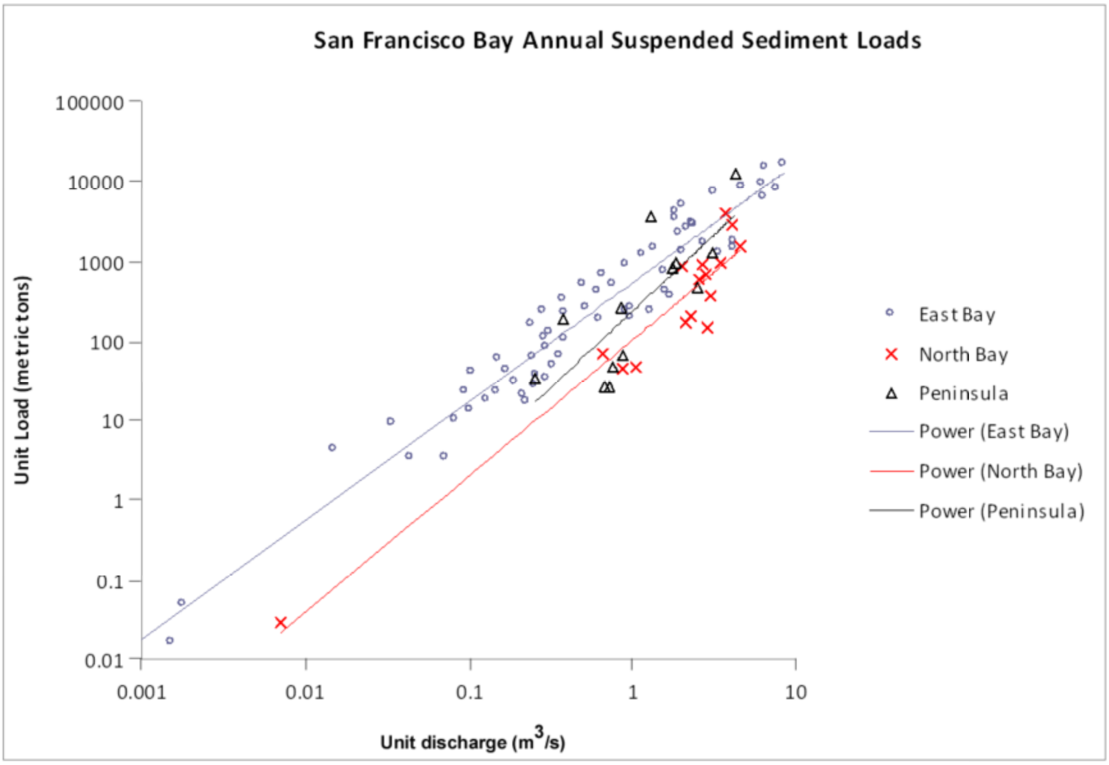

Figure 2. Annual peak discharge correlated with suspended sediment load for each geomorphologic province.

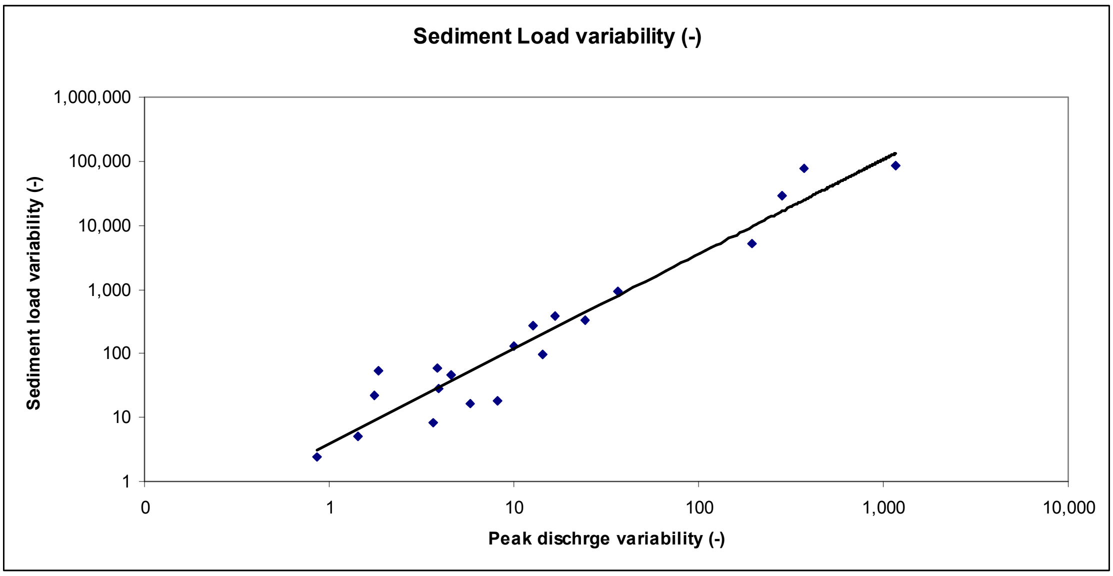

Figure 3. Dimensionless annual peak flow (Q_{max}/Q_{min})versus dimensionless annual peak load (Qs_{max}/Qs_{min}) within the monitored watersheds.

Table 5. Sediment loads and yields from selected watersheds based on USGS measurements of sediment load (watershed specific regressions) and the flow based method (estimates of peak flow based on the Rantz method and regional regressions for the North Bay, East Bay, and Peninsula).

Watershed	Total area (km^2)	Watershed load (t/yr)	Yield ($t/km^2/yr$)
East Bay			
Wildcat Creek Watershed	26	8,404	327
Mount Diablo Creek	32	10,050	318
Pinole Creek Watershed	38	11,771	309
San Pablo Creek Watershed	106	28,415	267
San Lorenzo Creek	125	32,732	261
San Leandro Creek	128	33,371	260
Walnut Creek	321	73,559	229
Coyote Creek	833	28,860	35
Alameda Creek	1688	108,798	64
North Bay			
Mill Creek	12	1,745	149
Corte Madera Creek	48	16,089	334
San Antonio Creek	80	7,752	97
Carneros Creek	22	2,817	127
Suisun Creek	134	11,656	87
Sonoma Creek	241	37,114	154
Napa River	738	43,075	58.4
Novato Creek	96	8,968	93
Petaluma River	122	10,853	89
Peninsula			
Guadalupe River	446	14,000	31
Permanente Creek	45	12,915	285
San Francisquito Creek	118	13,693	116
San Mateo Creek Watershed	86	21,914	254
Colma Creek Watershed	41	46,379	1,136

yield in Bay Area watersheds varied from 31 to 1,130 t/km^2 (Table 5). Greatest yields tended to occur in smaller, often steep, watersheds. For example, the Wildcat Creek watershed (11181390), with a watershed area of 26 km^2 had an estimated long term average annual yield of 327 t/km^2 whereas the Alameda Creek watershed (11179000), with a watershed area of 1,639 km^2 has a long term average annual yield of 64 t/km^2 (Table 5). The largest sediment yields were associated with two watersheds that were undergoing urbanization when the USGS was making measurements (e.g., Colma Creek watershed yield = 1,136 t/km^2; Zone 6 Line B watershed yield =13,493 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, annual average suspended sediment yield was estimated to vary from 44 to 788 t/km^2 (Appendix 3). Yields in these watershed areas are generally similar to those measured by the USGS although not as high as the yields measured by the USGS in some of steeper and small non-urban watersheds and certainly not as high as those measured in Colma Creek or Zone 6 Line B.

Regionally, the contemporary annual average sediment loads entering the Bay from local Bay Area watersheds in the nine-county Bay Area (an area of 8,180 km^2) is estimated to be 1,269,606 metric t. This is equivalent to an average of 155 metric t /km^2. A comparison of the two methods of calculation showed similar regional results (compare column 2 and column 3 of Table 6). For the most part (59%), the land use sediment yield based method was used to compute loads in the Peninsula due to this area having the greatest percentage of urban area and relatively small watersheds (Table 6). Regionally, however 35% of the load was calculated using the land use sediment yield based method in an area totaling 2,860 km^2 (Table 6). When summed for RMP Bay segments, we estimate that annual average suspended sediment loads from local small tributaries range between 214,900 and 270,200 metric t for the most urbanized Bay segments (Central Bay, South Bay and Lower South Bay) (Table 7). 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 from the nine-county Bay Area (Table 7).

Table 6. San Francisco Bay sediment input estimated by different methods.

Province	Land use based estimate (t/yr)	Flow / land use estimate (t/yr)	Percentage of the drainage area where loads were estimated with the land-use based method (%)
East Bay	590,604	717,308	45
North Bay	354,622	365,779	38
Peninsula	177,368	186,518	59
Entire Bay	1,122,594	1,269,606	35

Table 7. Suspended sediment inputs from local tributaries into the RMP Bay segments compared to average suspended sediment loads entering the Bay from the Central Valley (McKee et al., 2006).

RMP Bay Segment	Load (t/year)
Rivers	27,353
Suisun Bay	203,453
Carquinez Strait	25,693
San Pablo Bay	281,789
Central Bay	246,170
South Bay	270,202
Lower South Bay	214,940
Total	1,269,606
Central Valley via the Sacramento River at Mallard Island (McKee et al., 2006)	1,000,000

DISCUSSION

Estimates of suspended sediment loads entering San Francisco Bay from the local tributaries in the nine-counties surrounding the Bay Area have been studied in the past by a number of researchers. In our study, we explore and evaluate hydrologic, physical, and land-use characteristics of the San Francisco Bay watersheds in order to predict relationship between watershed sediment load and geomorphic processes and ultimately provide an updated estimate of regional suspended sediment loads from small tributaries.

We find that 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 the long, dry summers return the system to virtually the same condition by October in each year; each year can be considered independent from the preceding year (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 (McKee et al., 2003) would confound the correlation. This we find, 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 and Bolton, 1976; Milliman and Syvitski, 1992).

Watershed-specific sediment load is considered to be inversely related to drainage area (Vanoni, 2006; McKee et al., 2003). Available data illustrates that sediment loads have a weak correlation with drainage area. Our results improved to some degree when sites were sorted into the distinctive geomorphic provinces. Topography is another factor that generally is 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 on slope only. Our observation of this phenomenon is also in agreement with the observations made by some previous authors (e.g., Wenhong, 2004).

Bedrock resistance to erosion has a great impact on headwater and in-channel sediment production. As described in the methods, in our study erosional properties of Bay Area lithologies are classified based on the professional observations of Sarah Pearce about properties of bedrock. For example, the Napa watershed is composed of multiple lithologies, some of which are in the most resistant category (e.g., Sonoma Volcanics) whereas the west side of Napa is dominated by the Franciscan Formation which is in the least resistant category. The result is a classification of average erodability. In our analysis, there is very little improvement in predicting watershed sediment load if different types of bedrock resistance are used as predictors. It is possible that the impact of lithology is overshadowed here 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). There are spatial limitations in the current data set that make it impossible to test this statistically in the Bay Area. For example, the local landslide data set is challenged by differences in landslide definitions and classifications (Wentworth et al., 1997). In our load to peak discharge statistical correlations the sediment supplied by landslides and fire is already accounted for in the sediment data recorded by the USGS gages. Although landslides, debris flows, and wild fires are somewhat common in the Bay Area, at the watershed scale their signals appear to be dampened in the short time scale (<100 years) by factors such as hillslope and channel storage. At the Holocene time scale, these processes in many cases are responsible for an order of magnitude larger sediment inputs than all the other sources combined (Kirchner et al., 2001). While there may be hundreds or even thousands of these ephemeral features in a watershed, they tend not to be active all the time and their connectivity to the channel is variable. That said, there is evidence that when they are connected they can supply perhaps 80% of the total sediment load in a channel (e.g., Pearce et al., 2006)

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. The attempts to introduce additional variables to single-variable correlations did not improve the overall correlation. 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 non-linear and therefore it is difficult to detect statistically significant correlations between multiple variables in a variety of spatial and temporal settings. In addition, the quality of each of the spatial GIS data sets is variable, a second factor leading to limited ability at this time to develop a multi-parameter model for suspended sediment loads prediction for Bay Area small tributaries.

Our estimates represent long-term averages. Sources of uncertainty in our estimates come from three general types of limitations: 1) Measurement uncertainty of suspended sediment in the field and statistical errors in rating curve regressions; 2) uncertainty in construction of sediment load predictive equations; and 3) uncertainty in applied land use data. Some details of the above types of uncertainty include:

- There are inaccuracies related to generation of the peak-discharge estimates for the ungaged watersheds (Rantz, 1971);
- The analysis relies on sediment discharge regressions with coefficients of determination from 0.62 to 0.94;
- The frequency distribution of different magnitude peak flow events has a coefficient of determination of 0.76 (Table 8)[2];
- The uncertainty associated with land-use specific sediment production is the most difficult to estimate. However, the differences between the unit sediment load estimates obtained by application of the land-use-based method and the flow-based method are generally not greater than 30% and were always less than 21% when summed for each RMP Bay segment. Therefore we assume that this

Table 8. Accuracy associated with various statistical methods of the sediment load estimation.

Parameter	Coefficients of determination R^2

[2] This was determined by comparing the measured long term average peak flows from Napa and Alameda monitoring stations with the predicted

Peak discharge estimation error	0.95
Sediment discharge regression error	0.76
Measurements and rating curve error	0.75
Long term hydrograph error	0.76
Land use sediment production	0.75

number represents the probable range of inaccuracies associated with application of this method.

- The use of sediment rating curves to estimate sediment loads has inherent limitations due to monitoring program limitations (Horowitz, 2002). Usually, USGS sediment rating curves are developed by integrating continuous or near-continuous discharge with manually collected load samples collected at fixed time intervals. Continuous suspended sediment data is generally not available. Therefore, USGS sediment-load data generated from rating curves may have different levels of accuracy for various time periods and between watersheds (Horowitz, 2002). Typically, sediment rating curves under predict high sediment loads, and over predict low sediment loads. Such bias in the input data accuracy probably resulted in the underestimation of the total sediment loads entering the San Francisco Bay.
- Recent climate change that promotes more intense precipitation affects precision of predictions based on the sediment rating curves from stations with a long data record, since sediment dynamics change with changing climate and land-use characteristics.

Taking into account qualifiers about uncertainty, the results presented give insight not only into the long-term sediment loads. The annual error between the predicted and measured loads ranges between -82% and +122% and the average is approximately 6% or flow-weighted average is 9% (a slightly positive bias) for Alameda Creek (Table 9). For the Bay Area watersheds where there are USGS measured loads, a flow-weighted average of 13% is computed again a slightly positive bias but not statistically different to zero (See Appendix 4). 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. Generally, predictions that are within a factor of two of actual measurements are considered sufficient for a majority of the practical applications and based on the errors we have discussed, it appears that our estimates when summed to the regional as a whole may be accurate within +/- 50%.

Table 9. An example of the annual percent difference between USGS measured loads and yields in Alameda Creek and Niles (11179000) and estimated loads and yields based on an Alameda Creek specific regression (See appendix 4 for more examples).

Water Year	Watershed	Area (km^2)	Max annual peak discharge (m^3/s)	Measured annual load (metric t/yr)	Predicted Annual load (metric t/yr)	Sediment yield (metric $t/km^2/yr$)	Predicted sediment yield (metric t/km/yr)	% Error
1957	11179000	1,639	27	2,106	3,027	1.28	1.85	44
1958	11179000		722	760,410	870,649	463.81	531.26	14
1959	11179000		121	18,774	40,355	11.45	24.62	115
1960	11179000		60	14,674	12,181	8.95	7.43	-17
1961	11179000		1	9	5	0.01	0	-47
1962	11179000		95	36,784	26,578	22.44	16.22	-28
1963	11179000		326	163,405	221,924	99.67	135.42	36
1964	11179000		52	6,431	9,641	3.92	5.88	50
1965	11179000		151	99,569	59,094	60.73	36.06	-41
1966	11179000		21	5,745	2,075	3.5	1.27	-64
1967	11179000		385	260,780	295,962	159.06	180.59	13
1968	11179000		64	8,344	13,594	5.09	8.29	63
1969	11179000		178	146,757	78,992	89.51	48.2	-46
1970	11179000		197	79,417	93,263	48.44	56.91	17
1971	11179000		65	24,999	14,010	15.25	8.55	-44
1972	11179000		9	2,766	503	1.69	0.31	-82
1973	11179000		236	209,652	128,113	127.88	78.17	-39
2000	11179000		178	35,412	78,777	21.6	48.07	122
2001	11179000		45	5,462	7,434	3.33	4.54	36
2002	11179000		72	8,099	16,500	4.94	10.07	104
2003	11179000		294	394,341	186,747	240.53	113.95	-53
2004	11179000		170	89,675	73,062	54.7	44.58	-19
2005	11179000		101	41,933	29,940	25.58	18.27	-29
2006	11179000		286	150,401	177,597	91.74	108.37	18
2007	11179000		43	5,389	6,881	3.29	4.2	28

The estimate presented of the San Francisco Bay sediment input, excluding the Delta, indicates that the long term average input into the Bay is higher than previously believed (Krone, 1979; Porterfield, 1980; Krone 1996, Kondolf 2000; Abu Saba and Tang, 2000; Davis et al., 2000; McKee et al., 2003, Schoellhamer et al. 2005). The literature review completed by McKee et al. (2003) showed that previous estimates ranged between 320,000 and 1,000,000 metric t/yr (Table 10). There are several reasons why the estimates from the present study are greater than those of previous studies. The main reason was 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. Other authors used a simple area extrapolation to the ungaged watershed area (e.g., Krone, 1979; Porterfield, 1980; Krone 1996). The second significant reason was that more data

Table 10. Examples of previous estimation of suspended sediment loads entering the Bay from the local watersheds compared to the estimates from the present study.

Author	Suspended load (thousand metric t/yr)
Krone (1979)	934

Ogden Beeman and Associates (1992)	744
Russel et.al. (1980)	1,000
Davis et. al.(2000)	320
McKee et al. (2003)	561-604
This study (Lewicki and McKee, 2009)	1,270

was available covering a longer time period and greater climatic variation. This provided for a better estimate of suspended sediment loads during wet years. In some cases, previous estimates have been biased low because of the use of dry weather data (e.g., Davis et al., 2000). The last major reason for the present estimates being greater than previous estimates is the choice of the regional area. The present study used an area generated within our GIS database of 8,180 km^2. This differs from, for example, McKee et al. (2003) who extrapolated the then existing data to a regional area of 6,650 km^2 and discounted the area upstream from reservoirs (1,600 km^2) assuming complete trapping. It also differs from Davis et al. (2000) who also removed the area upstream from reservoirs from their calculations.

Our findings have several implications. San Francisco Bay is listed by the state of California as impaired for mercury, polychlorinated biphenyls (PCBs) and a variety of other hydrophobic trace metals and trace organic contaminants that readily absorb to fine sediments. Mercury and PCB contaminant management reports (TMDL reports) link water quality (concentrations and pollutant mass transport) to the supply and redistribution of fine suspended sediments in the Bay (Looker and Johnson, 2004; Hetzel, 2006). At present, the main method for estimating regional-scale contaminant loads is to combine particle concentrations (mass of contaminant per mass of sediment (mg/kg equivalent to grams of contaminant per metric t of suspended sediment)) with regional estimates of sediment loads. Therefore, any change in the estimates of regional scale suspended sediment loads implies a change in the estimates of regional scale contaminant loads. Here, our regional scale prediction is greater than previous predictions by at least 30%.

Each year, approximately three million cubic meters of sediment is dredged from San Francisco Bay to maintain deep water shipping channels and port facilities (BCDC, 2008). Fine sediment deposits on stream beds, reducing the bed complexity, changing the hydraulic properties of the bed, reducing hyporheic exchange, and dissolved oxygen flow, and degrading habitat for fish and invertebrates (e.g., Alonso et al., 1988; Bjormn and Reiser, 1991). Fine sediment impacts Bay habitat similarly, extirpating native species, smothering sea grasses, and providing habitat for non-native invasive species. Conversely, although some of the deposited and dredged sediment is contaminated, suspended sediment is an important resource for agencies and groups actively pursuing protection and restoration of wetlands and salt marshes, especially during sea level rise. These issues facing San Francisco Bay are not dissimilar to those facing other estuaries around the world where information on loads of fine suspended sediment also has been summarized in response to management needs (e.g., Eyre et al., 1998).

In the case of San Francisco Bay, suspended sediment supplied by local tributaries enters the Bay from literally hundreds of small watersheds and is likely deposited on the Bay margins. From there it is likely slowly reworked by tides, wind and currents into the axis of the Bay where it may be transported longer distances before being redeposited elsewhere in the Bay or offshore in the Pacific Ocean (Krone 1979). In addition to the large number of point inflows, the inability of freshwater inflows from small tributaries (estimated to be about 1km^3/year on average; McKee et al., 2003) to impact the salinity regime of the Bay, and thus the hydraulic flushing time, increases the potential for deposition near the tributary mouth. In contrast, sediment supplied from the Central Valley is supplied through one cross-section and the average inflow from the Central Valley is approximately 25 km^3 annually (McKee et al., 2006). Flows of this magnitude can flush some of the flood load suspended sediment offshore in a single event (Ruhl et al 2001, Oram and Nezlin, in preparation). The implication is that sediment supply from local small tributaries may have a larger impact on siltation in near shore marinas, shipping facilities, and wetlands than sediment from the Central Valley.

CONCLUSIONS

In our study, we explored and evaluated hydrologic, physical, and land-use characteristics of the San Francisco Bay watersheds in order to find spatial and temporal patterns in suspended sediment input to the San Francisco Bay from local watersheds. We developed suspended sediment load rating curves for all available stations with annual records. The results indicate that peak annual discharge combined with the land-use-specific sediment production has the best potential for successful prediction of sediment load from the San Francisco Bay watersheds. Construction of a multiple regression model failed due to insufficient available input data. Introduction of additional variables to the regression equation did not improve accuracy of the sediment loads predictions. As more sediment data are collected, the main geomorphic processes are better documented (i.e., slope-sediment delivery), and, as the spatial variables in the GIS layer are improved, the understanding of the relationship between local watershed characteristics and sediment loads may be improved with further effort in the future. Regionally, the new estimate of sediment loads entering the Bay from local Bay Area watersheds in the nine-county Bay Area (an area of 8,180 km^2) is estimated to be 1,269,606 metric t. This is equivalent to an average of 155 metric t/km^2.

Previous studies suggested lower sediment inputs entering the Bay from the local watersheds than what have been provided by our new work. We suggest that the predictions resulting from this study are more accurate and provide better information about explicit spatial dynamics in the sediment input from different sources and regions. Our results indicate that annual average suspended sediment loads entering the Bay from urbanized small tributaries in the nine-county Bay Area are greater than the average loads entering the Bay from the Central Valley.

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Appendix 1A. Annual peak discharge (m^3/s) for East Bay USGS gaging stations where there is a corresponding suspended sediment record.

Water Year	**Alameda Ck. At Niles** 11179000	**Arroyo De La Laguna at Verona** 11177000	**Alameda Ck. Below Welch Ck. Near Sunol** 11173575	**Arroyo Valle Near Livermore** 11176500	**Arroyo Valle Below Lang Canyon Near Livermore** 11176400	**Cull Ck. Above Cull Ck. Reservoir Near Castro Valley** 11180960	**Cull Ck. Below Cull Creek Dam Near Castro Valley** 11180965	**San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley** 11180825	**Crow Creek Near Hayward** 11180900	**San Lorenzo Ck. At San Lorenzo** 11181040	**Zone 6 Line B At Warm Springs Boulevard At Fremont** 11172365	**Walnut Ck. At Concord** 11183600	**Wildcat Ck. At Vale Road At Richmond** 11181390
1956	821												
1957	27												
1958	722												
1959	121												
1960	60			38									
1961	1			0.4									
1962	95			73									
1963	326			249									
1964	52			8	7								
1965	151			56	66								
1966	21			10	12								
1967	385			134	144								
1968	64			7	14					40			
1969	178			25	151					54		171	
1970	197	96		3	48					93		167	
1971	65	39		2	27					51		74	
1972	9	10		2	3					8		14	
1973	236	124		29	58					104		249	
1974	189	67		8	32					112		104	
1975	117	70		11	38					55		223	
1976	10	9		1	0.2					25		20	1

Appendix 1A (continued). Annual peak discharge (m^3/s) for East Bay USGS gaging stations where there is a corresponding suspended sediment record.

	Alameda Ck. At Niles	**Arroyo De La Laguna at Verona**	**Alameda Ck. Below Welch Ck. Near Sunol**	**Arroyo Valle Near Livermore**	**Arroyo Valle Below Lang Canyon Near Livermore**	**Cull Ck. Above Cull Ck. Reservoir Near Castro Valley**	**Cull Ck. Below Cull Creek Dam Near Castro Valley**	**San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley**	**Crow Creek Near Hayward**	**San Lorenzo Ck. At San Lorenzo**	**Zone 6 Line B At Warm Springs Boulevard At Fremont**	**Walnut Ck. At Concord**	**Wildcat Ck. At Vale Road At Richmond**
Water Year	**11179000**	**11177000**	**11173575**	**11176500**	**11176400**	**11180960**	**11180965**	**11180825**	**11180900**	**11181040**	**11172365**	**11183600**	**11181390**
1977	12	14		1	0.2					31		40	5
1978	112	95		31	98					74		173	17
1979	58	53		1	28	8	6			17		87	25
1980	292	166		61	162	18				29		193	36
1981	29	30		2	19	2		5		29		26	5
1982	360	323		55	199	48		33		108		377	58
1983	354	297		81	189	37		36		108		252	20
1984	150			7	55	11		12		150		104	8
1985	100			0	13	9		11		23		177	9
1986	464			62	249	27		41		110		238	32
1987	118			0.3	19	9		17		79		122	16
1988	42	54		0.7	3	1		6		154		96	2
1989	26	30		0.3	4	2		5		292		24	5
1990	68	71		0.3	2	0		9		89		127	6
1991	97	54		44	66	3		7		137		38	6
1992	94	69		0	60	5				58		134	8
1993	286	173		41	110	27		45		34			33
1994	37	29		2	5	1		5		112			9
1995	425	180		57	240	14				76			35
1996	250	112		58	116	11				56			30
1997	303	165		63	150	36				112			40

Appendix 1A (continued). Annual peak discharge (m^3/s) for East Bay USGS gaging stations where there is a corresponding suspended sediment record.

	Alameda Ck. At Niles	Arroyo De La Laguna at Verona	Alameda Ck. Below Welch Ck. Near Sunol	Arroyo Valle Near Livermore	Arroyo Valle Below Lang Canyon Near Livermore	Cull Ck. Above Cull Ck. Reservoir Near Castro Valley	Cull Ck. Below Cull Creek Dam Near Castro Valley	San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley	Crow Creek Near Hayward	San Lorenzo Ck. At San Lorenzo	Zone 6 Line B At Warm Springs Boulevard At Fremont	Walnut Ck. At Concord	Wildcat Ck. At Vale Road At Richmond
Water Year	**11179000**	**11177000**	**11173575**	**11176500**	**11176400**	**11180960**	**11180965**	**11180825**	**11180900**	**11181040**	**11172365**	**11183600**	**11181390**
1998	507	256		84	219	44		110	56				
1999	129	102		1	44	19		36	22				
2000	178	117	82	9	101	24		48	37		2		
2001	45	51	8	1	37	1		6	3		1		
2002	72	68	27	15	13	6		13	8		1		
2003	294	201	163	8	102	24		47	48				
2004	170		73	3	67	18		29	34				
2005	101		53	27	32	8		8	16				
2006	286		107	32	88	27		40	47				
2007	43			1	9								

Appendix 1B. Annual peak discharge (m^3/s) for San Francisco Peninsula (including south Bay) USGS gaging stations where there is a corresponding suspended sediment record.

	Guadalupe R. At San Jose	San Francisquito Ck. At Stanford	Colma Ck. At South San Francisco	Permanente Ck. Near Monte Vista	West Fork Permanente Ck. Near Monte Vista	Pescadero Ck. Near Pescadero	San Gregorio Ck. At San Gregorio	Coyote Ck. Above Highway 237 At Milpitas	Coyote Ck. Near Gilroy
Water Year	**11169025**	**11164500**	**11162720**	**11166575**	**11166578**	**11162500**	**11162570**	**11172175**	**11169800**
1956									
1957									
1958									
1959									
1960		29				23			
1961		0.3				4			1
1962		28				49			126
1963		93				190			286
1964		27	30			33			65
1965		32	19			94			151
1966		25	23			18			47
1967		113	32			116			195
1968		32	36			78			20
1969		65	33			82			232
1970		88	27			65	88		134
1971		28	56			22	45		36
1972		20	24			6	10		13
1973		96	82			152	106		140
1974		97	42			67	102		66
1975		62	26			49	57		63
1976		2	17			2	2		1
1977		2	57			2	1		1
1978		70	39			115	82		184

Appendix 1B (continued). Annual peak discharge (m^3/s) for San Francisco Peninsula (including south Bay) USGS gaging stations where there is a corresponding suspended sediment record.

	Guadalupe R. At San Jose	San Francisquito Ck. At Stanford	Colma Ck. At South San Francisco	Permanente Ck. Near Monte Vista	West Fork Permanente Ck. Near Monte Vista	Pescadero Ck. Near Pescadero	San Gregorio Ck. At San Gregorio	Coyote Ck. Above Highway 237 At Milpitas	Coyote Ck. Near Gilroy
Water Year	**11169025**	**11164500**	**11162720**	**11166575**	**11166578**	**11162500**	**11162570**	**11172175**	**11169800**
1979		38	39			54	52		71
1980		93	63			83	75		176
1981		18	28			18	35		142
1982		148	72			266	224		194
1983		97	46			214	154		
1984		48	56			0	45		
1985		64	46	1	0.1	48	70		
1986		99	76	16	4	149	109		
1987		44	41	1		20	77		
1988		20	1008			13	48		
1989		11	40			21	27		
1990		13	90			14	35		
1991		18	51			33	50		
1992		73	56			116	147		
1993		85	99			143	100		
1994		23	77			28	26		
1995		94				176	187		
1996		43	75			90	0.0		
1997		92				110	173		
1998		204				300	0		
1999		75				76	0	40	
2000		111				132	0	72	
2001		18				20	0	35	

Appendix 1B (continued). Annual peak discharge (m^3/s) for San Francisco Peninsula (including south Bay) USGS gaging stations where there is a corresponding suspended sediment record.

	Guadalupe R. At San Jose	San Francisquito Ck. At Stanford	Colma Ck. At South San Francisco	Permanente Ck. Near Monte Vista	West Fork Permanente Ck. Near Monte Vista	Pescadero Ck. Near Pescadero	San Gregorio Ck. At San Gregorio	Coyote Ck. Above Highway 237 At Milpitas	Coyote Ck. Near Gilroy
Water Year	**11169025**	**11164500**	**11162720**	**11166575**	**11166578**	**11162500**	**11162570**	**11172175**	**11169800**
2002		30				78	64	19	
2003	172	106				159	85	42	
2004	124	56				108	76	29	
2005	112	27				38	37	29	108
2006	95	137				169		48	211
2007		14				15		13	23

Appendix 1C. Annual peak discharge (m^3/s) for the North Bay USGS gaging stations where there is a corresponding suspended sediment record.

	Sonoma Creek At Agua Caliente	Sonoma Creek At Boyes hot spring	Pine Ck. At Bolinas	Corte Madera Ck. Near Ross	Napa R. Near Napa	Napa River Near Saint Helena	Lagunitas Ck. At Samuel P. Taylor State Park	Walker Ck. Near Marshall
Water Year	**11458500**	**11458500**	**11460170**	**11460000**	**11458000**	**11456000**	**11460400**	**11460750**
1956		251						
1957		41						
1958		179						
1959		133						
1960		185		74	348	328		
1961	65	65		15	95	61		
1962	157	157		76	257	219		
1963	133			70	708	348		
1964	123			29	149	142		
1965	213			40	513	334		
1966	232			82	314	260		
1967	220			88	606	314		
1968	163		7	48	244	141		
1969	234		20	53	248	187		
1970	186		28	93	416	268		
1971	238			75	345	275		
1972	18			26	40	32		
1973	250			76	394	320		
1974	122			55	276	189		
1975	196			75	306	242		
1976	6			9	9	6		
1977	3			4	2	4		
1978	201			62	433	283		
1979	202			40	179	70		
1980	167			82	354	204		
1981	86			34	135	104		
1982				170	592	283		
1983				99	490	303	74	413
1984				65	345	257	52	110
1985				74	265	209	51	30
1986				118	1051	479	98	200
1987				66	138	77	55	31
1988				28	65	39	25	20
1989				38	138	106	37	33
1990				17	53	39	17	11
1991				47	255	197	29	15
1992				51	132	82	48	14

Appendix 1C (continued). Annual peak discharge (m^3/s) for the North Bay USGS gaging stations where there is a corresponding suspended sediment record.

	Sonoma Creek At Agua Caliente	Sonoma Creek At Boyes hot spring	Pine Ck. At Bolinas	Corte Madera Ck. Near Ross	Napa R. Near Napa	Napa River Near Saint Helena	Lagunitas Ck. At Samuel P. Taylor State Park	Walker Ck. Near Marshall
Water Year	**11458500**	**11458500**	**11460170**	**11460000**	**11458000**	**11456000**	**11460400**	**11460750**
1993				95	368	225	59	143
1994					46	25	11	16
1995					923	314	85	192
1996					331	164	86	44
1997					527		100	124
1998					561		165	297
1999					256		53	112
2000					202		50	40
2001					122	93	14	7
2002	136				278	112	68	35
2003	211				541	289	74	62
2004	175				345	220	91	48
2005	124				172	394	50	27
2006	575				838	518	289	220
2007							25	

Appendix 2A. USGS gaging stations with suspended sediment data in the East Bay watersheds (metric t/yr).

	Alameda Ck. At Niles	Arroyo De La Laguna Near Pleasanton	Arroyo De La Laguna at Verona	Alameda Ck. Below Welch Ck. Near Sunol	Arroyo Valle Near Livermore	Arroyo Valle Below Lang Canyon Near Livermore	Cull Ck. Above Cull Ck. Reservoir Near Castro Valley	Cull Ck. Below Cull Creek Dam Near Castro Valley	San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley	Crow Creek Near Hayward	San Lorenzo Ck. At San Lorenzo	Zone 6 Line B At Warm Springs Boulevard At Fremont	Walnut Ck. At Concord	Wildcat Ck. At Vale Road At Richmond
Water Year	**11179000**	**11177000**	**11177000**	**11173575**	**11176500**	**11176400**	**11180960**	**11180965**	**11180825**	**11180900**	**11181040**	**11172365**	**11183600**	**11181390**
1956														
1957	2,106													
1958	760,410													
1959	18,774													
1960	14,674													
1961	9													
1962	36,784													
1963	163,405				52,293									
1964	6,431													
1965	99,569				15,592									
1966	5,745				485								7,747	
1967	260,780				133,938								211,105	
1968	8,344												12,519	
1969	146,757												109,680	
1970	79,417												160,574	
1971	24,999												100,336	
1972	2766													
1973	209652													
1974						8,037								

Appendix 2A (continued). USGS gaging stations with suspended sediment data in the East Bay watersheds (metric t/yr).

	Alameda Ck. At Niles	**Arroyo De La Laguna Near Pleasanton**	**Arroyo De La Laguna at Verona**	**Alameda Ck. Below Welch Ck. Near Sunol**	**Arroyo Valle Near Livermore**	**Arroyo Valle Below Lang Canyon Near Livermore**	**Cull Ck. Above Cull Ck. Reservoir Near Castro Valley**	**Cull Ck. Below Cull Creek Dam Near Castro Valley**	**San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley**	**Crow Creek Near Hayward**	**San Lorenzo Ck. At San Lorenzo**	**Zone 6 Line B At Warm Springs Boulevard At Fremont**	**Walnut Ck. At Concord**	**Wildcat Ck. At Vale Road At Richmond**
Water Year	**11179000**	**11177000**	**11177000**	**11173575**	**11176500**	**11176400**	**11180960**	**11180965**	**11180825**	**11180900**	**11181040**	**11172365**	**11183600**	**11181390**
1975						10,752								
1976						6								
1977						2								
1978						No data								19,222
1979						2,641	8,475	337						7,380
1980							43,038							37,780
1981							1,282		605					
1982							93,217		73664					
1983							87,180		88700					
1984							19,508		11810					
1985							4,186		3344					
1986							48,908		52075					
1987							2,359		3555					
1988							98		1147					
1989							280		499					
1990									No data					
1991									No data					
1992							1,328		5348		10,619			

Appendix 2A (continued). USGS gaging stations with suspended sediment data in the East Bay watersheds (metric t/yr).

	Alameda Ck. At Niles	**Arroyo De La Laguna Near Pleasanton**	**Arroyo De La Laguna at Verona**	**Alameda Ck. Below Welch Ck. Near Sunol**	**Arroyo Valle Near Livermore**	**Arroyo Valle Below Lang Canyon Near Livermore**	**Cull Ck. Above Cull Ck. Reservoir Near Castro Valley**	**Cull Ck. Below Cull Creek Dam Near Castro Valley**	**San Lorenzo Ck. Above Don Castro Reservoir Near Castro Valley**	**Crow Creek Near Hayward**	**San Lorenzo Ck. At San Lorenzo**	**Zone 6 Line B At Warm Springs Boulevard At Fremont**	**Walnut Ck. At Concord**	**Wildcat Ck. At Vale Road At Richmond**
Water Year	**11179000**	**11177000**	**11177000**	**11173575**	**11176500**	**11176400**	**11180960**	**11180965**	**11180825**	**11180900**	**11181040**	**11172365**	**11183600**	**11181390**
1993									No data					
1994									649					
1995							15,826		No data					
1996							12,560		No data					
1997							35,701		No data					
1998							45,291		167,013					
1999							7,081		23,510					
2000	35,412	43,355		13,887			8,116		29,797	34,908		19,700		
2001	5,462	7,145		109			132		605	356		8,404		
2002	8,099	16,764		1,441			1,496		73,664	3,145		906		
2003	394,341	207,295		8,230			10,216		88,700	28,241				
2004	89,675						8,475		11,810					
2005	41,933						43,038		3,344					
2006	150,401						1,282		52,075					
2007	5,389		7,043											
Count	25	4	1	4	4	5	24	1	20	4	1	3	6	3

Appendix 2B. USGS gaging stations with sediment data for the Peninsula watersheds (including the south Bay) (metric t/yr).

	Guadalupe R. At San Jose	**San Francisquito Ck. At Stanford**	**Colma Ck. At South San Francisco**	**Permanente Ck. Near Monte Vista**	**West Fork Permanente Ck. Near Monte Vista**	**Pescadero Ck. Near Pescadero**	**Coyote Ck. Above Highway 237 At Milpitas**	**Coyote Ck. Near Gilroy**
Water Year	**11169025**	**11164500**	**11162720**	**11166575**	**11166578**	**11162500**	**11172175**	**11169800**
1956								
1957								
1958								
1959								
1960								
1961								25,396
1962		1,705						90,700
1963		16,961						3,628
1964		998						37,187
1965		9,524						2,540
1966		998	29,242					71,254
1967		45,894	110,823					127
1968		2,449	32,423					152,648
1969		31,019	59,053					17,696
1970		13,693	22,571					1,491
1971			25,074					49
1972			5,614					26,411
1973			52,937					8,442
1974		13,693	23,411					5,617
1975			3,753					2
1976			2,068					
1977								
1978								
1979								
1980						43,115		
1981								
1982								
1983								
1984								
1985				722				
1986				48,306	11,016			
1987				127				
1988								
1989								
1990								
1991								
1992								
1993								
1994								

Appendix 2B (continued). USGS gaging stations with sediment data for the Peninsula watersheds (including the south Bay) (metric t/yr).

	Guadalupe R. At San Jose	**San Francisquito Ck. At Stanford**	**Colma Ck. At South San Francisco**	**Permanente Ck. Near Monte Vista**	**West Fork Permanente Ck. Near Monte Vista**	**Pescadero Ck. Near Pescadero**	**Coyote Ck. Above Highway 237 At Milpitas**	**Coyote Ck. Near Gilroy**
Water Year	**11169025**	**11164500**	**11162720**	**11166575**	**11166578**	**11162500**	**11172175**	**11169800**
1995								
1996								
1997								
1998								
1999								
2000								
2001								
2002								
2003	10,787							
2004	8,219						6,571	
2005	4,918						10,162	
2006	11,674						14,940	
2007							1,775	
Count	4	10	11	3	1	1	4	15

Appendix 2C. USGS gaging stations with suspended sediment data in the North Bay watersheds (metric t/yr).

	Sonoma Creek At Boyes Hot Spring	Pine Ck. At Bolinas	Corte Madera Ck. Near Ross	Napa R. Near Napa	Napa River Near Saint Helena	Lagunitas Ck. At Samuel P. Taylor State Park	Walker Ck. Near Marshall
Water year	**11458500**	**11460170**	**11460000**	**11458000**	**11456000**	**11460400**	**11460750**
1956	157,853						
1957	3,810						
1958	8,437						
1959	9,526						
1960	20,593						
1961	2,631						
1962	32,841				52,408		
1963							
1964							
1965							
1966							
1967							
1968		348					
1969		6,877					
1970		30,299					
1971							
1972							
1973							
1974							
1975							
1976							
1977				6.32			
1978			17,342	184,761			
1979			3,700				

Appendix 2C (continued). USGS gaging stations with suspended sediment data in the North Bay watersheds (metric t/yr).

	Sonoma Creek At Boyes hot spring	Pine Ck. At Bolinas	Corte Madera Ck. Near Ross	Napa R. Near Napa	Napa River Near Saint Helena	Lagunitas Ck. At Samuel P. Taylor State Park	Walker Ck. Near Marshall
Water year	**11458500**	**11460170**	**11460000**	**11458000**	**11456000**	**11460400**	**11460750**
1980			27,223				
1981							
1982							
1983							
1984			16,089				
1985							
1986							
1987							
1988							
1989							
1990							
1991							
1992							
1993							
1994							
1995							
1996							
1997							
1998							
1999							
2000							
2001							

Appendix 2C (continued). USGS gaging stations with suspended sediment data in the North Bay watersheds (metric t/yr).

	Sonoma Creek At Boyes hot spring	**Pine Ck. At Bolinas**	**Corte Madera Ck. Near Ross**	**Napa R. Near Napa**	**Napa River Near Saint Helena**	**Lagunitas Ck. At Samuel P. Taylor State Park**	**Walker Ck. Near Marshall**
Water year	**11458500**	**11460170**	**11460000**	**11458000**	**11456000**	**11460400**	**11460750**
2002							
2003							
2004						4,340	6,285
2005						1985	3,900
2006						33,339	717,867
2007							
Count	7	3	4	2	1	3	3

Appendix 3. Sediment load and yield from selected watersheds using the land use method (those where there are watershed names in the GIS data base).

Watershed	Total area (km^2)	Watershed load (t/yr)	Yield ($t/km^2/yr$)
Land use based method			
San Tomas	114.091	25,483	223
Stevens Creek	79.202	10,881	137
Lower Penitencia Creek	75.933	15,975	210
Agua Caliente Ck Lk Bliz	72.336	17,201	238
Old Alameda Creek	55.302	22,440	406
Calabazas Creek	52.863	15,801	299
Matadero Creek	30.985	7,101	229
Redwood Ck Arroyo Ojo	29.809	8,656	290
Estudillo Canal	29.462	10,196	346
Adobe Creek	28.963	5,380	186
Mowry Slough Fremont Newark	27.667	13,926	503
Flood Slough Watershed	22.962	5,528	241
Agua Fria Creek	20.454	5,947	291
San Pedro Creek Watershed	20.176	2,156	107
Sunnyvale West	18.635	6,476	348
Stevens Creek	17.980	8,099	450
Temescal Creek	17.617	4,397	250
Ardenwood Crandall Creek	16.887	7,617	451
Arroyo Viejo	16.260	4,700	289
Peralta Creek	14.654	6,412	438
Port of Oakland WS	14.064	2,208	157
Newark Slough Sanjon de	12.384	6,653	537
San Bruno Creek Watershed	11.845	4,206	355
Laurel Creek	11.705	4,408	377
Refugio Creek Watershed	11.603	3,045	262
Derby and Potter Creeks	10.954	6,345	579
Foster City Lagoon Water	9.922	4,491	453
Herman Slough Watershed	9.641	2,932	304
Pulgas Creek Watershed_1	9.376	2,186	233
Pulgas Creek Watershed_2	9.197	2,791	303
Lion Creek	9.079	2,879	317
Hayward Landing Canal	8.782	2,558	291
Meeker Slough Watershed	8.592	4,382	510

Appendix 3 (continued). Sediment load and yield from selected watersheds using the land use method (those where there are watershed names in the GIS data base).

Watershed	Total area (km^2)	Watershed load (t/yr)	Yield ($t/km^2/yr$)
Land use based method			
Belmont Creek Watershed	8.394	2,690	320
Piedmont Watershed_2	8.340	3,307	397
Ettie Street Pump Station	8.300	3,987	480
Strawberry Creek	8.090	2,393	296
Barron Creek	8.042	2,770	344
Borel Creek Watershed	8.010	2,990	373
Sulphur Creek	8.004	2,901	363
Terrace Creek Watershed	7.950	2,119	267
Cerrito Creek Watershed	7.918	3,330	421
Piedmont Watershed_1	7.781	3,212	413
Garrity Creek Watershed	7.733	3,331	431
Harbor Channel Waterhsed_2	7.603	2,872	378
Bockman Canal	7.602	3,705	487
Baxter Creek Watershed	7.471	3,586	480
Ravenswood Slough WS	7.442	3,058	411
Highline Canal Watershed	7.336	3,064	418
Vista Grande Canal Water	6.990	3,115	446
Guadalupe Valley Creek W	6.937	1,224	176
Mallard Slough	6.737	2,763	410
Elmhurst Creek	6.641	2,863	431
Glen Echo Creek	6.623	2,354	355
Plummer Ck (Summer Ck)	6.527	4,312	661
Ca±ada del Cierbo Watershed	6.447	816	127
Rheem Creek Watershed_1	5.307	2,589	488
Laguna Salada Watershed	4.858	941	194
Leslie Creek Watershed	4.801	2,581	537
Point Watershed	4.697	1,165	248
Davis Point Watershed	4.683	805	172
Sanchez Creek Watershed	4.666	1,411	302
Calera Creek Watershed	4.592	436	95
Redwood Shores Watershed	4.535	2,151	474
Cordonices Creek_2	4.304	1,910	444
Mills Creek Watershed	4.130	1,665	403

Appendix 3 (continued). Sediment load and yield from selected watersheds using the land use method (those where there are watershed names in the GIS data base).

Watershed	Total area (km^2)	Watershed load (t/yr)	Yield ($t/km^2/yr$)
Land use based method			
SFO Watershed A	4.118	375	91
Poplar Creek	4.034	1,980	491
El Portal Canal Watershed	3.993	1,641	411
SFO Watershed B	3.844	1,149	299
Point Richmond Peninsula West Watershed	3.713	1,036	279
Schoolhouse Creek	3.645	1,710	469
Coast Casey Forebay	3.606	1,814	503
Visitation Point	3.261	1,669	512
Oyster Point WS	3.208	1,116	348
Cordonices Creek_1	3.121	1,198	384
Salt Evaporators	3.096	417	135
Hoffman Channel Watershed	3.028	1,490	492
Seal Slough	3.008	1,528	508
San Bruno Mountain	2.922	370	127
Edgemar Watershed	1.137	607	534
Phelps Slough	2.785	1,180	424
Easton Creek Watershed	2.763	915	331
Moffat West	2.753	1,047	380
Milagra Creek Watershed	2.722	842	309
Giant Watershed	2.703	854	316
Bayshore Watershed	2.281	773	339
West Watershed	2.238	1,211	541
East Palo Alto Watershed	2.189	1,279	584
Laguna Alta	2.077	1,043	502
Airport Channel WS	2.037	768	377
Golf Course	1.767	722	409
Treasure Island	1.650	1,180	715
Coyote Point Watershed	1.590	892	561
Rheem West Watershed_2	1.416	542	383
Rockway Beach	1.390	208	149
Harbor Channel Waterhsed_1	1.386	744	537
Ward & Zeile Creeks (Upper Watershed)	1.385	1,057	763
Rodeo West Watershed	1.371	582	425

Appendix 3 (continued). Sediment load and yield from selected watersheds using the land use method (those where there are watershed names in the GIS data base).

Watershed	Total area (km^2)	Watershed load (t/yr)	Yield ($t/km^2/yr$)
Land use based method			
Gilman Street Watershed	1.368	553	404
Mussel Rock Watershed	1.330	458	345
San Leandro Bay WS	1.312	340	259
Belmont Slough	1.202	489	407
Point San Pedro Watershed	1.166	51	44
Sharp Park Watershed	1.056	337	319
Ninth Avenue	1.048	719	685
Lake Mathilda	0.998	506	507
Marina Lagoon	0.977	685	702
Emeryville Watershed	0.880	324	368
Point Richmond Peninsula North Watershed	0.836	119	142
Cooley Landing Watershed	0.811	484	596
Coliseum Watershed	0.706	372	527
Burlingame Lagoon	0.636	375	590
Treatment Plant	0.631	116	184
Yerba Buena Island Water	0.576	144	251
Sunnyvale West	0.570	215	377
Lake Merritt North WS	0.567	333	587
Pt San Bruno A	0.563	223	396
66th Avenue WS	0.496	75	152
Pt San Bruno C	0.493	213	431
Crow Creek_1	0.044	2	50
Pt San Bruno B	0.428	227	530
Pt San Bruno E	0.419	139	331
Ravenswood Point WS	0.370	108	291
Pt San Bruno G	0.287	131	457
Poplar Creek outfall	0.225	104	462
Pacifica Beach Watershed	0.222	64	290
Hercules Creek Watershed	0.198	91	459
Pt San Bruno D	0.172	68	398
Burlingame Drivein	0.167	112	671
Crow Creek_2	0.145	6	44
Albany Hill Watershed	0.137	84	616

Appendix 3 (continued). Sediment load and yield from selected watersheds using the land use method (those where there are watershed names in the GIS data base).

Watershed	Total area (km^2)	Watershed load (t/yr)	Yield ($t/km^2/yr$)
Land use based method			
Pt San Bruno F	0.130	30	230
Oyster Point Watershed	0.058	27	464
Smith Slough drain	0.044	35	788
Marina Lagoon drain	0.032	24	734

Appendix 4. Annual percent error - measured and estimated loads and yields for watersheds where there are long term loads measurements made by the USGS.

Water Year	Watershed	Area (km^2)	Max annual peak discharge (m^3/s)	Measured annual load (metric t/yr)	Predicted Annual load (metric t/yr)	Sediment yield (metric $t/km^2/yr$)	Predicted sediment yield (metric t/km^2yr)	% Error
1957	11179000	1639	27	2,106	3,027	1.28	1.85	44
1958	11179000		722	760,410	870,649	463.81	531.26	14
1959	11179000		121	18,774	40,355	11.45	24.62	115
1960	11179000		60	14,674	12,181	8.95	7.43	-17
1961	11179000		1	9	5	0.01	0	-47
1962	11179000		95	36,784	26,578	22.44	16.22	-28
1963	11179000		326	163,405	221,924	99.67	135.42	36
1964	11179000		52	6,431	9,641	3.92	5.88	50
1965	11179000		151	99,569	59,094	60.73	36.06	-41
1966	11179000		21	5,745	2,075	3.5	1.27	-64
1967	11179000		385	260,780	295,962	159.06	180.59	13
1968	11179000		64	8,344	13,594	5.09	8.29	63
1969	11179000		178	146,757	78,992	89.51	48.2	-46
1970	11179000		197	79,417	93,263	48.44	56.91	17
1971	11179000		65	24,999	14,010	15.25	8.55	-44
1972	11179000		9	2,766	503	1.69	0.31	-82
1973	11179000		236	209,652	128,113	127.88	78.17	-39
2000	11179000		178	35,412	78,777	21.6	48.07	122
2001	11179000		45	5,462	7,434	3.33	4.54	36
2002	11179000		72	8,099	16,500	4.94	10.07	104
2003	11179000		294	394,341	186,747	240.53	113.95	-53
2004	11179000		170	89,675	73,062	54.7	44.58	-19
2005	11179000		101	41,933	29,940	25.58	18.27	-29
2006	11179000		286	150,401	177,597	91.74	108.37	18
2007	11179000		43	5,389	6,881	3.29	4.2	28
2004	11172175	826	29	6,571	4,642	7.95	5.62	-29
2005	11172175		29	10,162	4,642	12.3	5.62	-54
2006	11172175		48	14,940	9,827	18.08	11.9	-34
2007	11172175		13	1,775	1,397	2.15	1.69	-21

Appendix 4 (continued). Annual percent error - measured and estimated loads and yields for watersheds where there are long term loads measurements made by the USGS.

Water Year	Watershed	Area (km^2)	Max annual peak discharge (m^3/s)	Measured annual load (metric t/yr)	Predicted Annual load (metric t/yr)	Sediment yield (metric t/km^2/yr)	Predicted sediment yield (metric t/ km^2/yr)	% Error
1977	11458000	565	2	6	65	0.08	0.12	930
1978	11458000		433	184,761	324,652	2193.61	574.82	76
2003	11169025	414	172	10,787	17,574	26.03	42.43	63
2004	11169025		124	8,219	10,077	19.83	24.33	23
2005	11169025		112	4,918	8,406	11.87	20.29	71
2006	11169025		95	11674	6,400	28.17	15.45	-45
1962	11169800	282	126	25,396	13,590	90.06	48.21	-46
1963	11169800		286	90,700	55,495	321.63	196.86	-39
1964	11169800		65	3,628	4,345	12.87	15.41	20
1965	11169800		151	37,187	18,465	131.87	65.5	-50
1966	11169800		47	2,540	2,475	9.01	8.78	-3
1967	11169800		195	71,254	28,854	252.67	102.36	-60
1968	11169800		20	127	568	0.45	2.02	347
1969	11169800		232	152,648	38,724	541.3	137.37	-75
1970	11169800		134	17,696	15,036	62.75	53.34	-15
1971	11169800		36	1,491	1,579	5.29	5.6	6
1972	11169800		13	49	261	0.17	0.93	430
1973	11169800		140	26,411	16,372	93.66	58.08	-38
1974	11169800		66	8,442	4,476	29.94	15.88	-47
1975	11169800		63	5,617	4,119	19.92	14.61	-27
1969	11183600	221	171	109,680	128,443	3329.16	581.41	17
1970	11183600		167	160,574	124,290	4873.96	562.61	-23
1971	11183600		74	100,336	36,752	3045.53	166.36	-63
1992	11181040	116	58	10,619	6,790	91.58	58.56	-36
1962	11164500	97.0	28	1,705	2,120	17.58	21.86	24
1963	11164500		93	16,961	37,770	174.85	389.53	123
1964	11164500		27	998	1,881	10.29	19.4	89
1965	11164500		32	9,524	2,817	98.18	29.05	-70
1966	11164500		25	998	1,571	10.29	16.2	57
1967	11164500		113	45,894	61,540	473.13	634.68	34
1968	11164500		32	2,449	2,878	25.25	29.68	18
1969	11164500		65	31,019	16,103	319.79	166.07	-48
1981	11180825	46.6	5	605	1,516	12.97	32.53	151
1982	11180825		33	73664	23,272	1580.1	499.39	-68
1983	11180825		36	88700	27,352	1902.62	586.92	-69
1984	11180825		12	11810	5,041	253.33	108.16	-57
1985	11180825		11	3344	4,698	71.73	100.82	40
1986	11180825		41	52075	33,355	1117.02	715.73	-36
1987	11180825		17	3555	9,056	76.26	194.33	155
1988	11180825		6	1147	2,028	24.6	43.52	77
1989	11180825		5	499	1,189	10.7	25.51	138
1994	11180825		5	649	1,211	13.91	25.99	87
1998	11180825		110	167013	146,202	3582.44	3137.25	-12
1999	11180825		36	23510	26,710	504.28	573.15	14
2000	11180825		48	29797	42,332	639.14	908.37	42

Appendix 4 (continued). Annual percent error - measured and estimated loads and yields for watersheds where there are long term loads measurements made by the USGS.

Water Year	Watershed	Area (km^2)	Max annual peak discharge (m^3/s)	Measured annual load (metric t/yr)	Predicted Annual load (metric t/yr)	Sediment yield (metric $t/km^2/yr$)	Predicted sediment discharge (metric $t/km^2/yr$)	% Error
1966	11162720	28.0	23	29,242	18,039	7005.58	644.51	-38
1967	11162720		32	110,823	28,974	26549.99	1035.18	-74
1968	11162720		36	32,423	34,606	7767.68	1236.39	7
1969	11162720		33	59,053	31,346	14147.32	1119.94	-47
1970	11162720		27	22,571	22,748	5407.36	812.75	1
1971	11162720		56	25,074	68,416	6007	2444.37	173
1972	11162720		24	5,614	18,675	1344.95	667.21	233
1973	11162720		82	52,937	120,379	12682.15	4300.9	127
1974	11162720		42	23,411	43,662	5608.56	1559.95	87
1975	11162720		26	3,753	21,044	899	751.87	461
1976	11162720		17	2,068	11,590	495.38	414.07	460
2000	11180900	27.2	37	34,908	37,675	1283.6	1385.89	8
2001	11180900		3	356	679	13.1	24.96	91
2002	11180900		8	3,145	3,635	115.64	133.73	16
2003	11180900		48	28,241	55,175	1038.48	2029.65	95
1978	11181390	20.0	17	19,222	13,109	6447.33	655.71	-32
1979	11181390		25	7,380	24,718	2475.41	1236.39	235
1980	11181390		36	37,780	42,043	12671.64	2102.95	11
1979	11180965	16.5	6	337	3,102	20.46	188.11	819
1979	11180960	15.0	8	8,475	4,761	565.12	317.59	-44
1980	11180960		18	43,038	17,030	2869.93	1136.08	-60
1981	11180960		2	1,282	730	85.47	48.68	-43
1982	11180960		48	93,217	73,995	6216.07	4936.18	-21
1983	11180960		37	87,180	49,817	5813.53	3323.26	-43
1984	11180960		11	19,508	7,580	1300.85	505.68	-61
1985	11180960		9	4,186	5,875	279.12	391.91	40
1986	11180960		27	48,908	31,339	3261.39	2090.59	-36
1987	11180960		9	2,359	6,073	157.32	405.12	157
1988	11180960		1	98	323	6.54	21.54	229
1989	11180960		2	280	569	18.69	37.97	103
1992	11180960		5	1,328	2,654	88.55	177.08	100
1995	11180960		14	15,826	10,984	1055.32	732.73	-31
1996	11180960		11	12,560	8,139	837.56	542.93	-35
1997	11180960		36	35,701	48,093	2380.71	3208.29	35
1998	11180960		44	45,291	65,581	3020.2	4374.91	45
1999	11180960		19	7,081	18,874	472.18	1259.05	167
2000	11180960		24	8,116	25,831	541.21	1723.18	218
2001	11180960		1	132	169	8.81	11.3	28
2002	11180960		6	1,496	2,895	99.79	193.1	93
2003	11180960		24	10,216	25,877	681.24	1726.27	153
1985	11166575	10.0	1	722	463	484.37	46.36	-36
1986	11166575		16	48,306	17,699	32404.01	1770.59	-63
1987	11166575		1	127	251	85.41	25.15	97