# Measuring flood output from 110 coastal watersheds in California with field measurements and SeaWiFS

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## ABSTRACT

**The 1300-km-long California coast receives output from watersheds that range from ~10 km$^2$ within the coastal mountain ranges to ~120 000 km$^2$ for the drainage basins of the Sacramento and San Joaquin Rivers. Results from a combination of field and remote-sensing data, modeling, and digital techniques show that during the El Niño winter of 1998, the impact of sediment and water transport on nearshore waters from coastal watersheds was spatially extensive, varied with depth, and was comparable to the impact of output from large rivers. The mass of sediment estimated from SeaWiFS data for 25 discrete and coalesced buoyant river plumes emanating from 110 watersheds was 2.2 × 10$^6$ t. Although the mass of all of the plumes represents only 1%–2% of the total sediment output from the rivers, the plumes covered an area of 29 500 km$^2$ of coastal waters. An important cautionary note is that the surface plumes visible in the remote-sensing data (even though nearly coincident with flooding) do not represent mass output from the rivers.**

## INTRODUCTION

The first systematic quantification of water and sediment delivery to the world's oceans (Milliman and Meade, 1983) emphasized the output from large rivers. More recently, analysis of data from 280 rivers (Milliman and Syvitski, 1992) showed that the transfer of sediment to the ocean from steep, coastal watersheds is significantly underestimated because (1) the sediment yield is high for small rivers (e.g., 1400 $t \cdot km^{-2} \cdot yr^{-1}$ for the Santa Clara River and 1700 $t \cdot km^{-2} \cdot yr^{-1}$ for the Eel River in California) compared to large rivers (e.g., 120 $t \cdot km^{-2} \cdot yr^{-1}$ for the Mississippi River), (2) small river flood plains do not store proportionally as much sediment as large river flood plains (Dunne et al., 1998; Phillips, 1989), and (3) mountainous coastal watersheds typically have small or nonexistent coastal landforms such as deltas and estuaries that can filter out sediment (Smith et al., 1996; Holligan and de Boois, 1993).

The dispersion of sediment from river mouths (Wright, 1977; Wright and Nittrouer, 1995) varies vertically as a function of the buoyancy of the river water (Chao, 1998; Mulder and Syvitski, 1995; Wright et al., 1988). Most large rivers of the world produce positively (hypopycnal) buoyant plumes (Wright and Nittrouer, 1995) that are readily observed with remote sensing data (Dinnel et al., 1990; Rouse and Coleman, 1976; Stumpf et al., 1993; Walker, 1996). These surface plumes are in contrast to the neutrally (homopycnal) and negatively (hyperpycnal) buoyant density currents that develop at the mouths of rivers with sufficiently high sediment concentrations (Bates, 1953). California coastal waters with an average salinity of 34‰ and average temperature of 15 °C yield a seawater density of 1025 $kg \cdot m^{-3}$. Therefore, a homopycnal plume with a density of 1025 $kg \cdot m^{-3}$ would contain 25 $kg \cdot m^{-3}$. Previously reported concentration data from several California rivers (Brownlie and Taylor, 1981; Geyer et al., 2000; Inman and Jenkins, 1999; Wheatcroft et al., 1997) indicate that many are capable of supporting both homopycnal and hyperpycnal flows during floods (Wheatcroft, 2000). In addition to whether there may be homopycnal or hyperpycnal flows, the evolution of surface plumes is influenced by river discharge (Hoekstra et al., 1989), coastal geography (Mertes et al., 1998), coastal climate (Walker, 1996), wind direction (Geyer et al., 2000), and tidal forcing (Dinnel et al., 1990).

In this paper we report analysis of sea-viewing wide field-of-view sensor (SeaWiFS) data combined with field measurements to examine the spread and composition of river water along the coast of California. The data are reported for the El Niño conditions during the winter of 1997–1998 that led to enhanced storm activity along the California coast. The techniques are generally applicable, but a cautionary message is that the observed surface plumes do not represent the mass output from the coastal rivers.

## MATERIALS AND METHODS

During six storm events (>3 cm rainfall), from December 1997 to February 1998, surface water samples were collected in a weighted Niskin bottle from bridges near the coast for two to 13 rivers in central California (northwest of the area indicated for the Santa Clara and Ventura Rivers in Fig. 1) and filtered onto tared 0.47 μm Millipore filters; the filters were weighed for total suspended matter (TSM). Particle size analysis of the sediments was performed with a Micromeritics Sedigraph (Coakley and Syvitski, 1992). On February 11, 1998, surface samples for TSM were collected at nine stations in the ocean within the river plume of the Santa Clara and Ventura Rivers. To characterize the vertical structure of the plume at each station, conductivity, temperature, salinity, and light transmission were measured with a Sea-Bird CTD (sensor for conductivity, temperature, and depth).

An image was acquired by the sea-viewing wide field-of-view sensor (SeaWiFS) for February 9, 1998, that was clear from the northern state border of California to just south of the Los Angeles area (Fig. 1). Using the SeaWiFS data, we produced a map of sediment concentration (milligrams per litre) based on a methodology developed by Mertes et al. (1993) for calibration to laboratory data. Satellite radiance was calculated by applying the time-dependent radiometric calibration to the raw sensor data (Eplee and Barnes, 2000). The extraterrestrial solar irradiance was corrected for Earth to sun distance (Gregg et al., 1993) and solar zenith angle as calculated from the SeaWiFS orbital geometry. Satellite (top of the atmosphere) reflectance of each SeaWiFS spectral band was calculated as the product of $\pi$ and the measured satellite radiance divided by the extraterrestrial solar irradiance for each band. Nominal path radiance, based on radiance over open-ocean water, was subtracted from all eight SeaWiFS bands to yield surface reflectance after insuring minimal aerosol variability across the image by using the band ratio 765/865 (Ruddick et al., 2000). To minimize the effect of variable absorption by dissolved organic matter on the reflectance signal in the blue and green bands (Toole and Siegel, 2001), bands at wavelengths 555, 670, 765, and 865 nm only were selected to convert the surface reflectance to sediment concentration in milligrams per litre. An error analysis of the nonlinear calibration curve produced an average predicted error for TSM of $\pm 10$ $mg \cdot L^{-1}$.

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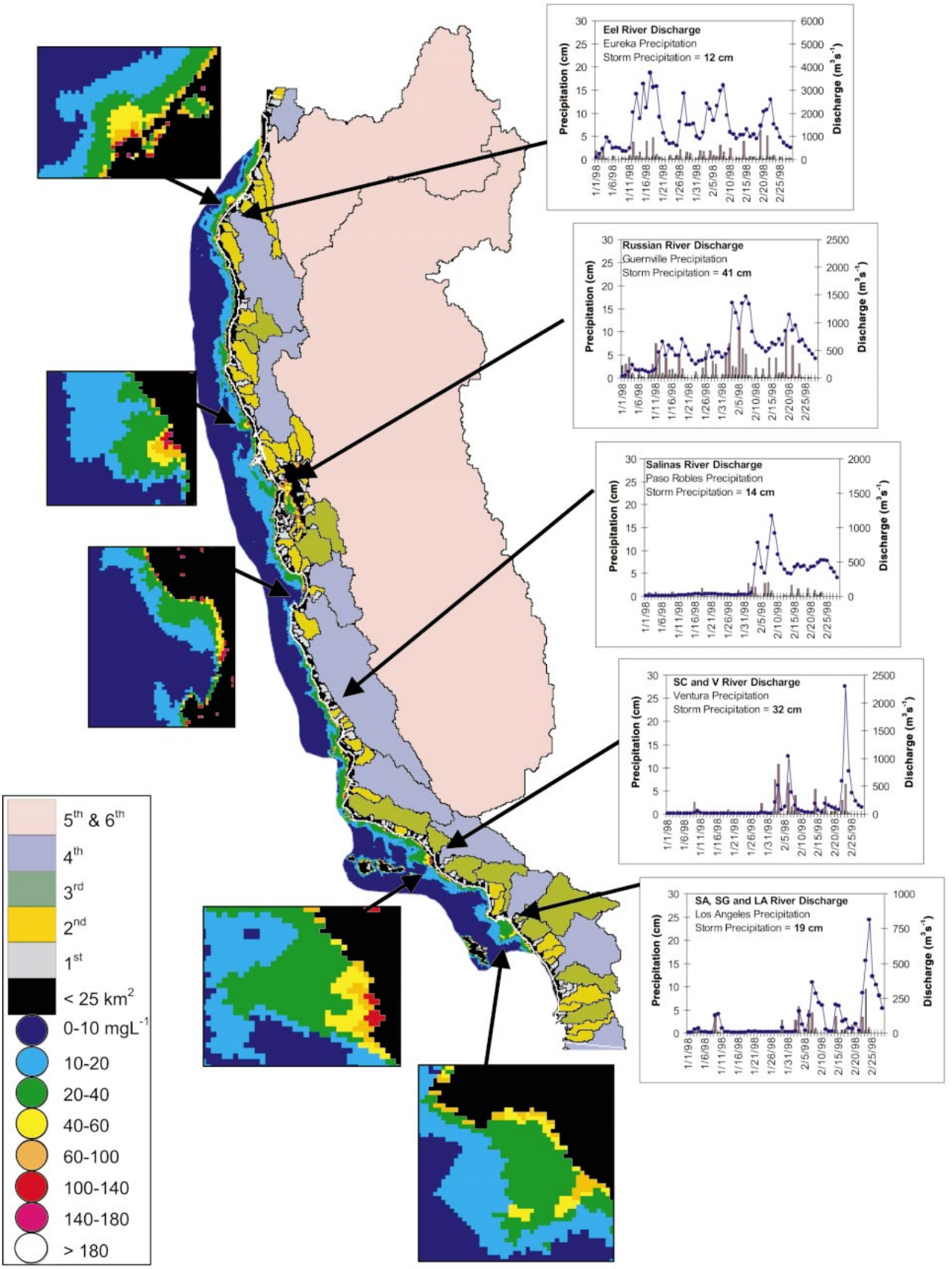


**Figure 1. Coastal river plumes for California, February 9, 1998. Precipitation and river discharge reported for January–February 1998; storm total in centimeters calculated for February 1–9, 1998. Total suspended matter for sediment plumes with concentrations ranging from 0 to 180 mg·L$^{-1}$ is based on spectral mixture analysis (Mertes et al., 1993) of SeaWiFS data. Watershed order is based on Strahler analysis (Mertes et al., 1998) for stream order from Hydro1K (U.S. Geological Survey), minimum watershed size >25 km$^2$. Individual pixels in plume details are 1 km$^2$. Drainage basin area, plume mass, and plume area are for Eel River (7430 km$^2$, 96 000 t, and 1034 km$^2$), Russian River**

Each of the surface plumes was assigned to their source rivers within a geographical information system (GIS) analysis that combined the image data with maps of watershed boundaries (Fig. 1) that were delineated using digital elevation data and standard algorithms for terrain analysis (Mertes et al., 1998). Ocean plumes were matched to watersheds by proximity to river mouths. To show relative size, watershed order was assigned subjectively, on the basis of the requirement that a first-order watershed is at least 25 $km^2$.

## RESULTS

During 1998, California experienced the wettest February of the past 100 years (National Climate Data Center, 1998). Most precipitation stations recorded over 400% of average February monthly precipitation, with exceptions in the Sierra Madre and Northern Coastal Range, which had over 200% of average monthly precipitation (National Climate Data Center, 1998). The storm of February 1–9, 1998 (Fig. 1), was most intense along the central coast of California (Russian River to Santa Clara River), where most stations received amounts of precipitation for a 10-year to 20-year (some up to 100-year—e.g., Monterey) recurrence interval (California Department of Water Resources, 1982; National Climate Data Center, 1998). South of this region, storm recurrence statistics showed slightly over five-year return intervals. North of the Russian River, storm precipitation amounts were near the annual average.

Field measurements of river TSM showed a range of sediment concentrations from 36 $g \cdot L^{-1}$ for the Santa Clara River (drainage basin area of 4100 $km^2$) to a maximum of 57 $g \cdot L^{-1}$ for Padre Juan Creek (approximate drainage basin area of 12 $km^2$). Texture analysis yielded a mean (5 $\mu$m) and modal (16 $\mu$m) grain size for the Santa Clara River in the silt range, as reported earlier by Inman and Jenkins (1999). These river-mouth measurements confirm that these California coastal watersheds produce the requisite sediment concentrations of $>25$ $g \cdot L^{-1}$ for hyperpycnal flows.

On the basis of our oceanographic measurements, the thickest part of the Santa Clara–Ventura surface plume (5 m) was associated with the highest measured concentration of TSM (44 $mg \cdot L^{-1}$), both thickness and concentration decreasing to 1.5 m and 2 $mg \cdot L^{-1}$ as the distance from the shoreline increased. These measurements of TSM and thickness of the surface plume are similar to data reported for the Eel River plume (Geyer et al., 2000; Hill et al., 2000), Yellow River plume (Wright et al., 1988), Mississippi River plume (Walker, 1996), and model results for hyperpycnal plumes (Chao, 1998).

On the basis of the SeaWiFS data, surface sediment concentrations ranged from open-ocean values of $<10$ $mg \cdot L^{-1}$ to 180 $mg \cdot L^{-1}$ near river mouths (Fig. 1). The higher concentrations derived from the image data in the Santa Clara–Ventura plume, compared to our field measurements (maximum 44 $mg \cdot L^{-1}$), are expected, because the image was acquired near the time of peak discharge for the rivers (Fig. 1), whereas the field measurements in the ocean were collected two days later, after some settling and dilution had occurred. The SeaWiFS image shows a total of 25 plumes that represent 110 coastal watersheds. Coalesced surface plumes emanating from multiple watersheds were included. Figure 1 shows details for the five largest plumes that were observed.

## DISCUSSION

Using the surface suspended-sediment concentrations (in milligrams per liter) derived directly from SeaWiFS data, we can examine the relationships among plume mass, plume size, and watershed size for the entire region. In order to calculate the total mass in all the surface plumes for February 9, 1998, the thickness of the surface plume for different sediment concentrations was estimated from the field measurements made in the Santa Clara–Ventura plume. The thickest part of the plume was calculated to be 5 m for concentrations $>25$ $mg \cdot L^{-1}$, decreasing to 4 m for 10–25 $mg \cdot L^{-1}$, and 3 m for 5–10 $mg \cdot L^{-1}$. For each 1 $km^2$ SeaWiFS pixel, a thickness was assigned according to the concentration, and the thickness was multiplied by the concentration and the area to yield mass in tons. The largest plume mass of 231 000 t was produced by the San Francisco Bay drainage, which has a watershed area of $\sim$120 000 $km^2$. The combined mass of 25 discrete plumes was calculated to be 2 200 000 t.

We made an order-of-magnitude estimate for total sediment output from the 110 watersheds by comparing the water discharge of the 1998 storm sequence (Fig. 1) to previously reported sediment-discharge data (Brownlie and Taylor, 1981; Griggs, 1987; Thornton, 1981; Wheatcroft et al., 1997). We estimated that the magnitude of the total suspended sediment discharge for the 110 coastal rivers represented by the 25 plumes was 100–200 $\times 10^6$ t. Thus, the sediment in the surface plumes represents only 1%–2% of the total river output. We used established sediment rating curves (Brownlie and Taylor, 1981) and reported water discharges (USGS Station 11114000 and 11118500) to make a more detailed estimate for the Santa Clara and Ventura Rivers. The total combined suspended-sediment discharge for the first week of February 1998 was $\sim 19 \times 10^6$ t, whereas the combined Santa Clara–Ventura surface plume contained only 82 700 t, or 0.4%, of the total suspended sediment load. Thus, remote sensing of these surface plumes cannot be used to estimate mass of sediment discharged by these rivers.

The results reported here can also be compared to field measurements taken during flood events on the Eel River plume during 1997 and 1998, which show that sediment concentration varied with depth, river discharge, wind direction, and distance from the river mouth (Geyer et al., 2000). Loss of sediment from the Eel River surface plumes through particle settling was apparently augmented by flocculation of particles (Hill et al., 2000), and these flocculated particles were deposited within hours. The results reported here confirm the rapid evolution of the Eel River plume in that, although the SeaWiFS image described in this study was recorded within hours of the peak flow on February 9 (Fig. 1), the observed surface plume also did not contain much of the mass output from the river.

Although the mass represented by these surface plumes is small, the areal extent of the 25 plumes was 29 500 $km^2$, the largest plumes extending tens of kilometers out from the coast (Fig. 1). The largest watersheds were seen to produce the largest plumes, yet the relative areal impact of the smaller watersheds was much greater (Fig. 2). The spatial extent of many of the smaller plumes was of the same order of magnitude or larger than their source watershed area; i.e., the ratio of surface plume area and watershed area had values $>1.0$. For comparison, this ratio for the $\sim$323 000 $km^2$ of the 110 California watersheds is much larger (0.13) than the ratio of 0.006 for the largest plume (13 000 $km^2$) reported from the Mississippi River watershed ($3.5 \times 10^6$ $km^2$) by Walker (1996).

## CONCLUSIONS

For the wet conditions of February 1998, coastal rivers in the central California area carried loads ranging up to $\sim$60 $g \cdot L^{-1}$ at their mouths. In contrast, the 25 relatively dilute surface plumes observed in calibrated SeaWiFS data for nearly the entire California coast typically showed maximum concentrations between 100 and 200 $mg \cdot L^{-1}$ and therefore contained remarkably little of the discharged suspended sediment (1%–2%) from the associated 110 coastal watersheds. Yet, plume extent into the nearshore waters (nearly 30 000 $km^2$) averaged

**(4870 $km^2$, 88 900 t, and 1160 $km^2$), Salinas River (16 642 $km^2$, 83 030 t, and 1158 $km^2$), Santa Clara (SC) and Ventura (V) rivers (4750 $km^2$, 82 665 t, and 792 $km^2$), and Santa Ana (SA), San Gabriel (SG), and Los Angeles (LA) rivers (8220 $km^2$, 137 565 t, and 1423 $km^2$).**

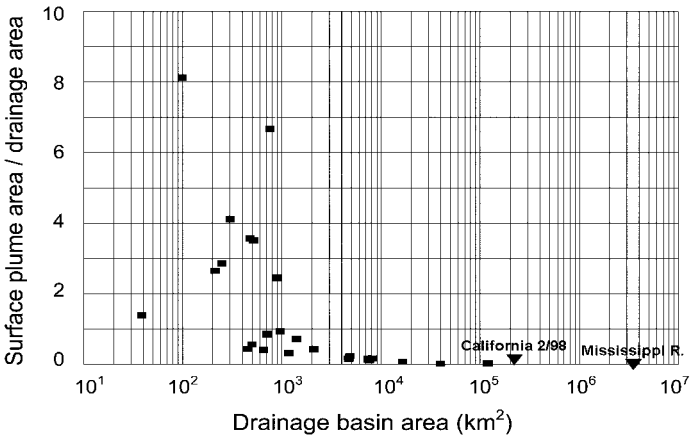


**Figure 2. Ratio of surface plume area to drainage basin area. California coast (California 2/98) and Mississippi River (Mississippi R.) ratios are shown for comparison.**

30 km out from the coast, the smaller watersheds having disproportionately larger plumes. Although our study combined timely field sampling and remote-sensing data acquisition, a quantitative mass balance of sediment delivery to nearshore waters remains elusive. Where river outputs are able to support particle flocculation, homopycnal, or hyperpycnal flows, remote sensing of surface plumes, even when acquired within hours of flooding events, cannot be used to calculate mass output from coastal rivers.

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