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# Eel River margin source-to-sink sediment budgets: Revisited

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ABSTRACT

The Eel River coastal margin has been used as a representative source-to-sink sediment dispersal system owing to its steep, high-sediment yield river and the formation of sedimentary strata on its continental shelf. One finding of previous studies is that the adjacent continental shelf retains only ~25% of the Eel River fine-grained sediment (less than 63 μm) discharged over time scales of both individual floods and the 20th century, thus suggesting that the Eel shelf trapping-efficiency is uniquely lower than other similar systems. Here I provide data and analyses showing that sediment discharge relationships in the Eel River have varied strongly with time and include substantial decreases in suspended-sediment concentrations during the latter 20th century. Including these trends in margin-wide sediment budgets, I show that previous Eel River sediment discharge rates were overestimated by a factor of two. Thus, revised sediment budgets shown here reveal that the Eel shelf retained ~50% of the discharged river fine-grained suspended sediment during intensively sampled events of 1995–97 and over the 20th century. In light of this, hypotheses about high rates of sediment export away from the primary shelf depocenter should be reevaluated.



## 1. Introduction

During the past two decades there have been strong research interests in marine sediment source-to-sink processes, which include the patterns of sediment movement from small, high-sediment yield rivers to marine depocenters (Nittrouer, 1999; Wheatcroft, 2000; Brunskill, 2004; Trincardi and Syvitski, 2005; Nittrouer et al., 2007; Carter et al., 2010). These studies are important because they characterize a class of rivers that was traditionally overlooked in marine geology, even though these watersheds discharge the majority of sediment to the world's oceans (Milliman and Syvitski, 1992; Milliman and Farnsworth, 2011). Studies of these small, high-sediment yield rivers have also resulted in a new appreciation for the nature and abundance of sediment transport phenomena such as wave-, current-, and gravity-supported sediment gravity flows (e.g., Mulder and Syvitski, 1995; Traykovski et al., 2000; Wright et al., 2001; Scully et al., 2003; Warrick and Milliman, 2003; Harris et al., 2005; Wright and Friedrichs, 2006; Friedrichs and Scully, 2007; Parsons et al., 2007; Traykovski et al., 2007; Hsu et al., 2009; Lamb and Mohrig, 2009; Carter et al., 2012; Liu et al., 2012), confirming and adding to the elements of early conceptual models by Bates (1953) and Moore (1969).

The Eel River margin (Fig. 1) has been the focus of multi-investigator sediment source-to-sink studies, including STRATA FORmation on Margins (STATAFORM) that was conducted in the mid- to late 1990s (Nittrouer, 1999; Wheatcroft, 2000; Nittrouer et al., 2007). The primary goal of these studies was to better understand the processes and interrelationships between river sediment supply, sediment transport phenomena, sediment deposition and accumulation, and marine sedimentary strata formation. Sediment mass balances from the river to the sea over time scales ranging from river floods to millennium were also developed from these observations. A key finding from the Eel River margin sediment mass balances was that the primary location of sediment deposition, the adjacent continental shelf (Fig. 1), incorporated only ~25% of the discharged river fine-grained sediment (less than 63 μm) over both river-event and centennial time scales (Wheatcroft et al., 1997; Wheatcroft and Borgeld, 2000; Crockett and Nittrouer, 2004; Hill et al., 2007; Sommerfield et al., 2007). The remaining ~75% of the river fine-grained sediment, while never fully accounted for, was hypothesized to be transported to the adjacent slope and submarine canyon as well as farfield regions of the shelf via across- and alongshore sediment transport phenomena (Harris et al., 2005; Wheatcroft and Sommerfield, 2005; Hill et al., 2007). It was hypothesized, therefore, that sediment dispersal patterns from the Eel River were uniquely different from surrounding rivers of the region that retain the majority (~60–80%) of the river fine-grained sediment on the shelf (Wheatcroft and Sommerfield, 2005; Sommerfield et al., 2007).

Recent evaluation of river sediment discharge measurements from the six largest coastal watersheds of northern California, including the Eel River, revealed that the suspended-sediment concentrations in all rivers exhibited strong and coherent time-dependent patterns, which included substantial increases during and following the massive December 1964 floods and steady decreases during the decades that followed (Warrick et al., 2013). These changes in river sediment

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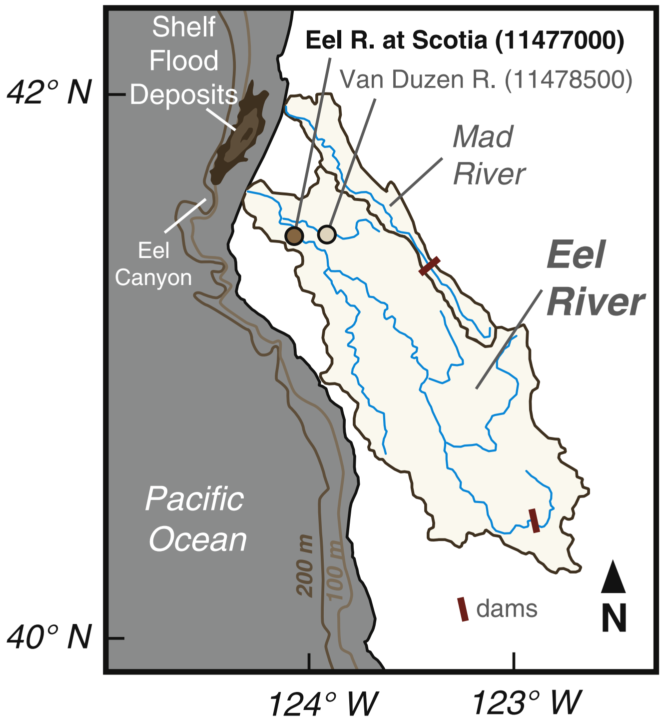


**Fig. 1.** Map of the Eel River study area showing the watershed, USGS river sampling stations (filled symbols), and flood sediment deposits on the continental shelf (shading) as defined by sedimentation during the 1995–1997 water years by Wheatcroft and Borgeld (2000).

discharge were consistent with the land use and climatic history of the region that are also expressed in hydrologic and geomorphic conditions of these watersheds (e.g., Kelsey, 1980; Lisle, 1982; Best, 1995; Best et al., 1995; Nolan and Janda, 1995; Madej and Ozaki, 1996; Leithold et al., 2005; Madej and Ozaki, 2009; Klein and Anderson, 2012; Madej et al., 2012). Furthermore, these changes resulted in strongly time-dependent river discharge–sediment concentration relationships, which are often described as sediment "rating curves" when used to estimate river sediment fluxes (Warrick et al., 2013). In light of this, one of the conclusions of Warrick et al. (2013) was that the Eel River margin source-to-sink sediment budgets "*may need to be reevaluated*" (p. 121), because previous sediment budgets did not fully include time-dependent sediment rating curves.

Here discharge and suspended-sediment information from the Eel River are used to reevaluate the source-to-sink sediment budgets developed from STRATAFORM program results. Three high flow events from 1995 and 1997 are highlighted, owing to the intensive marine coring efforts following these events that adequately characterized the spatial distribution of sediment for source-to-sink sediment mass balances (Wheatcroft et al., 1997; Wheatcroft and Borgeld, 2000; Hill et al., 2007). The 20th century sediment budgets developed from marine sediment inventories of $^{137}$Cs and excess $^{210}$Pb (cf. Alexander and Simoneau, 1999; Sommerfield and Nittrouer, 1999; Wheatcroft and Sommerfield, 2005; Mullenbach and Nittrouer, 2006; Sommerfield et al., 2007) were also reevaluated.

## 2. Data and methods

### 2.1. River sediment discharge

The mass of fine-grained suspended sediment discharged from the Eel River was assessed using U.S. Geological Survey (USGS) records of water discharge, discharge-weighted suspended-sediment concentrations, grain-size distributions of these suspended-sediment samples, and suspended-sediment discharge estimates. Calculations described below were conducted to directly compare with the sediment mass balances of Sommerfield and Nittrouer (1999), Wheatcroft and Borgeld (2000), Wheatcroft and Sommerfield (2005), Hill et al. (2007), and Sommerfield et al. (2007) that included considerations for the fine-grained (<63 μm) portion of the suspended-sediment discharge, corrections for logarithmic-transform bias (Ferguson, 1986), and scaling to estimate sediment discharge from the unmonitored watershed areas of the Eel and Mad Rivers.

#### 2.1.1. River discharge

The primary USGS stream gauge for the Eel River watershed is at Scotia (USGS Station 11477000), which incorporates over 85% of the ~9400 km$^2$ watershed drainage area (Fig. 1). This stream gauge has been active since October 1910 and has over a century of average daily discharge observations. These daily data provide the basis of the 20th century sediment discharge estimates by others (cf. Sommerfield et al., 2007) and those made in this study (Table 1).

To generate records of the total discharge from the Eel River, estimates of river water discharge from the remaining 15% of the watershed not captured by the Scotia gauge were needed. The techniques of Wheatcroft and Borgeld (2000) were used to fill these gaps, which use discharge in the Van Duzen River at Bridgeville gauge (USGS station 11478500) to represent flow from the ungauged landscapes. Consistent with Wheatcroft and Borgeld (2000), the Van Duzen River discharge was doubled and added to the discharge records from Scotia. No temporal lag was included in this summation. Discharge in the Van Duzen River was not measured before water year 1951 (water years are defined to extend from the 1st of October to the 30th of September and are named by calendar year for which they end; i.e., "water year 1951" is 1 October 1950 to 30 September 1951), and total Eel River discharge before this date was estimated by applying the discharge-weighted scaling factor of 1.23 to the Scotia discharge values to estimate additional discharge contributions from the total "ungauged" watershed (i.e., total Eel River discharge = 1.23 × Scotia).

In addition, the USGS gauge at Scotia was inoperable during three days of the January 1995 high flow event. For the days that discharge data were not available (8–11 January 1995), discharge at Scotia was estimated by linearly scaling the USGS discharge measurements at Eel River at Fort Seward (USGS station 11475000) by a factor of 1.28 to match the 9 January 1995 peak discharge of 10,400 m$^3$/s estimated by the USGS for the Scotia gauge. The interpolated records were also lagged by 7 h to incorporate the mean travel time of flood waves between these measurement locations. Combined, these interpolation techniques were consistent with methods of Wheatcroft et al. (1997) and Wheatcroft and Borgeld (2000).

Final estimates of total discharge from the Eel River were generated at 15-minute intervals for three high flow events of 1995–97, and at daily intervals for the records spanning water years 1911–2000 (Table 1). These time intervals were defined to match records used for sediment mass balances generated by previous researchers (Table 1).

#### 2.1.2. River suspended-sediment concentrations

Discharge-integrated samples of suspended sediment from the USGS Scotia gauge (USGS Station 11477000) provided another important variable for the sediment discharge estimates. It is important to note that several forms of suspended-sediment data are collected and available from the USGS. Between the water years 1955 and 1998, the USGS collected 460 suspended-sediment concentration samples at the Scotia gauge using standard discharge-integrated sampling techniques (cf. Guy and Norman, 1970; Edwards and Glysson, 1999). Although these samples were distributed across 44 water years, the sampling was not distributed evenly year-to-year (Fig. 2). All of these samples were analyzed for total suspended-sediment concentration, and the majority of these samples were analyzed for grain-size distribution information, which generally included weight-based percents of sediment finer than phi-based sediment diameters. The most commonly analyzed grain-size fraction was the mud-sand transition at 63 μm,

**Table 1**
Summary of the time intervals used to generate sediment mass balances for the Eel River margin.

| Event date | Time interval of river sediment discharge estimates | USGS discharge measurement frequency used in estimates | Primary comparative marine sediment deposition studies |
|---|---|---|---|
| January 1995 | 5–21 Jan 1995 (17 days) | 15 min | Wheatcroft and Borgeld (2000); Hill et al. (2007) |
| March 1995 | 7–19 Mar 1995 (12 days) | 15 min | Wheatcroft and Borgeld (2000); Hill et al. (2007) |
| January 1997 | 26 Dec 1996–10 Jan 1997 (15 days) | 15 min | Wheatcroft and Borgeld (2000); Hill et al. (2007) |
| Water years 1911–2000 ("20th century") | Water years 1911–2000[a] (88 years) | 1 d | Alexander and Simoneau (1999); Sommerfield and Nittrouer (1999); Wheatcroft and Sommerfield (2005); Mullenbach and Nittrouer (2006); Sommerfield et al. (2007) |

[a] Discharge was not measured or estimated for water years 1915–1916.

which was used to calculate the fine-grained suspended-sediment concentration of each sample by multiplication (i.e., fine-grained concentration = total concentration × fraction fine-grained). Both total and fine-grained suspended-sediment concentrations measured by the USGS expressed positive relationships with respect to river discharge (Fig. 3a,b).

From these suspended-sediment samples the USGS produced daily estimates of mean suspended-sediment concentration and total suspended-sediment discharge for the water years 1960–1980 (Fig. 2). The techniques used to generate these daily estimates are described in Portertield (1972), and they include graphical interpretation, use of historical records, additional data such as turbidity, and user expertise with the river system in question. A compilation of the 6666 daily mean suspended-sediment concentration estimates for the Eel River at Scotia is shown in Fig. 3c. These daily samples were used by previous sediment budget investigations by assuming a fine-grained fraction of ~75% (e.g., Wheatcroft and Borgeld, 2000).

With these different sources of suspended-sediment data, it is important to describe some of the strengths and weaknesses of each. For example, although the field measurements have a clear advantage of being physical samples of the river, they must be used in some interpretive manner – such as those found in Portertield (1972) or with sediment rating curves (e.g., Asselman, 2000; Horowitz, 2003) – to generate estimates of daily or annual sediment discharge. Additionally, although the majority of field measurements focused on the winter storm conditions when the majority of sediment is discharged, sampling strategies have changed with time, especially after 1980 when somewhat regular bimonthly samples were added to the sampling schedules to better characterize water quality conditions of the Eel River. This resulted in more samples during summer and low flow conditions following water year 1980, which has the potential to bias the sampling results and interpretations made from these data.

The daily data, in contrast, provide what are likely the best estimates of day-to-day river conditions during 1960 to 1980. Because of the strong user controls in the generation of these data, however, they are difficult to reproduce identically from rating curve or other technique. Furthermore, daily data do not cover the complete sediment sampling record (Fig. 2), so there are water years, including 1955–1959 and 1981–present, that have no daily data. Another limitation of the daily data is their lack of grain-size distribution information, which requires the user to generate assumptions about grain-size distributions if this information is needed (as it is in the present study).

It is also important to note that previous studies have used different sources of USGS suspended-sediment data. For example, previous margin-wide sediment mass balances were based on the daily mean data and rating curve relationships fit through these data (e.g., Wheatcroft et al., 1997; Wheatcroft and Sommerfield, 2005; Fig. 3c). Most river studies, in contrast, have used a combination of daily and field measurement data (e.g., Klein and Anderson, 2012; Warrick et al., 2013). This study uses both sources of USGS data, and an additional source as well, as described below.

One final source of suspended-sediment concentration data exists for the Eel River, surface water grab samples by academic researchers (Geyer et al., 2000; Goñi et al., 2013). While these kinds of samples have the potential to underestimate total suspended-sediment concentrations by not incorporating the middle and lower portions of the stream water profile where sediment concentrations are greatest (Edwards and Glysson, 1999), Rouse profile computations shown in the Part I of the Supplemental Information show that the total sediment concentrations measured by these researchers are *overestimates* of discharge-weighted fine-grained sediment concentrations by at least 13%. Thus, it is reasonable to use these surface water field samples as surrogates for the fine-grained suspended sediment concentrations that are the focus of this paper, as long as their slight positive bias is acknowledged.

All sources of suspended-sediment data described above were used in this study to investigate the magnitude and patterns of sediment discharge. In general, the USGS daily data were used for sediment discharge and trend analyses during the 1960–1980 water years. Field measurements – both USGS and other water surface samples – were used to evaluate trends in fine-grained suspended-sediment discharge both during and outside the interval of 1960–1980.

### 2.1.3. River sediment discharge calculations

For years without daily USGS sediment discharge data, suspended-sediment discharge at time, $t$, ($Q_s(t)$) was estimated by multiplying total river discharge of the Eel River ($Q$) by bias-corrected suspended-sediment concentrations ($C_s$):

$$Q_s(t) = Q(t)C_s(t). \quad (1)$$

The specific manner of estimating $C_s(t)$ will be described more fully in the Results section after a synthesis of the trends and patterns in the suspended-sediment data is presented. In general, however, nonlinear sediment rating curve techniques were evaluated to find one that best fits the patterns in the concentration data. This is consistent with the application of sediment rating curves in the previous studies, such as the modified power-law curve used by Wheatcroft and Borgeld (2000), which is shown in Fig. 3c. However, as shown below and in Part II of the Supplemental Information, the relationship between the log-transformed discharge and sediment concentration data were found to have curvature. Under these conditions Helsel and Hirsch (1991) suggest using the LOWESS (locally weighted scatterplot smoothing) regression function of Cleveland (1979), which was found to better represent the curvature as noted in the Supplemental Information.

Because of the strong trends in suspended-sediment concentrations with time, it was determined that the patterns expressed in the 1960–1980 daily data did not represent the suspended-sediment transport conditions during the years before and after these records. Sediment discharge estimates were then generated for each of the three high flow events of 1995–97 and for the entire 20th century by correcting for the time-dependent trends with simple linear correction factors. Uncertainties in the sediment discharge estimates were calculated by summation of the error of each estimate, which conservatively assumed that errors may be dependent over the records of each hydrologic event. The 1911–2000 values of annual sediment discharge were multiplied by a factor of 1.15 to incorporate the additional sediment discharge by the Mad River to the continental shelf, consistent with

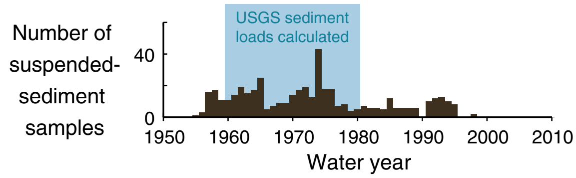


**Fig. 2.** A histogram showing the annual river suspended-sediment sampling rates by the USGS of the Eel River at Scotia gaging station (USGS 11477000). Also highlighted with lighter shading are the 1960–1980 water years, which have USGS daily estimates of sediment discharge based on the samples.

techniques of Sommerfield et al. (2007). Finally, all suspended-sediment discharge calculations used bias corrections of Ferguson (1986), which is consistent with the findings and calculations of previous studies (e.g., Wheatcroft and Borgeld, 2000; Sommerfield et al., 2007; Warrick et al., 2013).

### 2.2. Marine sedimentation

Rates of sedimentation used for sediment mass balances were taken directly from coring studies and summaries of Sommerfield and Nittrouer (1999), Wheatcroft and Borgeld (2000), Wheatcroft and Sommerfield (2005), Hill et al. (2007), and Sommerfield et al. (2007), some of which included additional measurements and results from Alexander and Simoneau (1999), Crockett and Nittrouer (2004), and Mulllenbach and Nittrouer (2006). As summarized in Tables 1 and 2, sedimentation rates are based on hundreds of cores that incorporate tens to hundreds of measurements of geophysical and geochemical parameters a piece. Sedimentation rates for the three events of 1995–97 were derived using sediment $^{7}$Be activities and mass accumulation inventories from samples obtained primarily from box corers (Wheatcroft and Borgeld, 2000). In contrast, sedimentation rates for the 20th century were based primarily on a combination of sediment $^{137}$Cs and excess $^{210}$Pb (Sommerfield and Nittrouer, 1999). The published rates of marine sedimentation were not revised for this analysis.

Sampling density and timing by these various coring efforts varied, making modern sediment budgets imperfect (e.g., see discussion in Sommerfield et al., 2007). However, the greatest sampling density of the Eel River margin was largely within the mid- to outer continental shelf near the river mouth (Table 2), where the fine-grained sediment depocenter was found centered between 60 and 100 m water depth (cf. Fig. 1). The 20th century sedimentation rates were much better constrained than the three events of 1995–97 owing to the dozens of cores placed throughout the entire margin (i.e., inner shelf to slope and farfield shelf; Table 2). In fact, the 1995–97 events were sampled only within the mid- to outer shelf sediment depocenter, no box coring was conducted in the other regions of the margin (Table 2). Event-response coring was conducted within the head of the Eel Canyon during water years 1998–2000 by Mullenbach et al. (2004), and although these data are informative of the general patterns and rates of sedimentation in the canyon region, they do not specifically constrain the 1995–97 sediment budgets.

## 3. Results

### 3.1. Sediment discharge trends — 1960–1980

It is instructive to examine the USGS daily suspended-sediment data for time-dependent patterns, because these trends – if they exist – are important to incorporate into sediment discharge calculations. As noted by Sommerfield et al. (2002) the daily sediment concentrations during water year 1965 were considerably higher with respect to discharge than in previous years. These changes in suspended-sediment concentration can be observed graphically in Fig. 4a and b. Yet, careful examination of the daily data also reveals decreases in sediment concentrations during the years following 1965 that match or exceed the increases that occurred during 1965 (Fig. 4c,d).

These trends were evaluated using several techniques. First, the USGS records of annual suspended-sediment discharge were compared with annual suspended-sediment discharge computed from a stationary (i.e., time-independent) sediment rating curve. The simplest manner to do this was to use a published rating curve, and here I use the modified power-law rating curve generated by Wheatcroft and Borgeld (2000) and shown in Fig. 3c. The results from this rating curve are shown for comparative purposes, and it is emphasized that results generated by any stationary sediment rating curve would be similar to those shown below. Second, a time series of expected suspended-sediment concentrations for specific river discharge values were generated using the weighted-regression techniques of Hirsch et al. (2010). These techniques were used to evaluate winter flow conditions within a year of the water year in question by setting the annual, seasonal and discharge weighting factors to: 3 years, 0.5 years, and 1

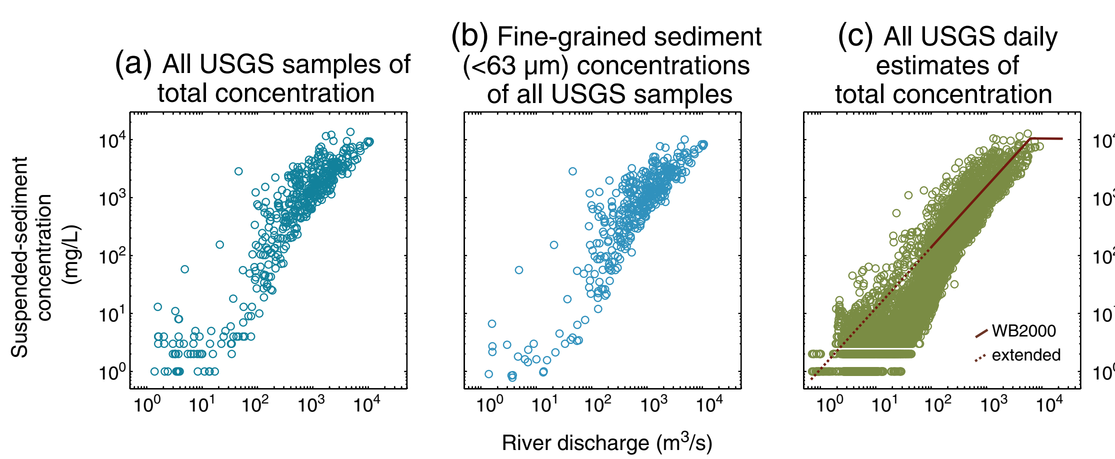


**Fig. 3.** Scatter plots of USGS river suspended-sediment concentrations and river discharge from the Eel River at Scotia gaging station (USGS 11477000). (a) All physical samples of suspended-sediment concentration. (b) A subset of the physical samples for which grain-size distributions were measured showing fine-grained sediment concentrations. (c) Estimated daily concentrations by the USGS for water years 1960–1980. Also shown in (c) is the sediment rating curve used by Wheatcroft and Borgeld (2000) "WB2000", which was extended below 100 m$^3$/s for the load estimates discussed below.

**Table 2**
Marine sedimentation measurements from cores included in the across-margin sediment mass balance.

| Sedimentation interval of time | Inner shelf (20–50 m) | Mid- to outer shelf (50–110 m) | Continental slope (110–800 m) | Canyon (100–850 m) | Far-field shelf (70–110 m) |
|---|---|---|---|---|---|
| *Number of cores obtained within region of margin*[a] | | | | | |
| January 1995 | n.a. | 63[b] | n.a. | n.a.[c] | n.a. |
| March 1995 | n.a. | 29[b] | n.a. | n.a.[c] | n.a. |
| January 1997 | n.a. | 45[b] | n.a. | n.a.[c] | n.a. |
| 20th century | 50[d] | 42[e] | 60[f] | 52[g] | 36[h] |
| *Measured rate of sedimentation (Mt/yr)* | | | | | |
| January 1995 | n.a. | 6.2[b] | n.a. | n.a. | n.a. |
| March 1995 | n.a. | 2.5[b] | n.a. | n.a. | n.a. |
| January 1997 | n.a. | 6.7[b] | n.a. | n.a. | n.a. |
| 20th century | 1.9[i] | 3.8[i] | 3.8[i] | 2.3[i] | n.a.[j] |

Notes: "n.a." = not applicable.
[a] The number of cores are either the number reported by the authors in the text of the report or (if the number was not reported) the number of unique symbols plotted in published maps of coring stations.
[b] Wheatcroft and Borgeld (2000).
[c] Sixty-seven box cores were obtained and analyses for event-scale sedimentation rates and patterns during water years 1998–2000 by Mulllenbach et al. (2004).
[d] Crockett and Nittrouer (2004).
[e] Sommerfield and Nittrouer (1999).
[f] Alexander and Simoneau (1999).
[g] Mulllenbach and Nittrouer (2006).
[h] Wheatcroft and Sommerfield (2005).
[i] Sommerfield et al. (2007).
[j] Although Wheatcroft and Sommerfield (2005) measured sedimentation rates on the continental shelf far from the Eel River, it is not apparent if this sediment was derived from the Eel or other regional rivers.

$\log_{10}$ unit of discharge (see Hirsch et al. (2010) for more details). Data collected outside of these ranges are not considered in each model output, which were generated for a midwinter date (31st of January) and a range of discharge values as noted below.

Annual sediment discharge estimates from the USGS and the stationary rating curve were most different during water year 1965, during which USGS sediment discharge was ~3-times greater than the rating curve estimate (Fig. 5a,b). These results are consistent with patterns and implications of the 1965 water year floods described by Sommerfield et al. (2002). It is not until water year 1969 that the two techniques result in similar values (i.e., the ratio is ~1), such as was previously observed during 1960–1964 (Fig. 5a,b). Interestingly, the utility of a stationary sediment rating curve declines during the 1970s as shown by a general decline in the ratio between the two sediment discharge estimates (Fig. 5b). These decreases are of such magnitude that by the end of the decade, the actual sediment discharge values reported by the USGS were ~70% of those estimated by a stationary rating curve (Fig. 5b).

These decreasing trends in suspended-sediment discharge with respect to river discharge are also exhibited in daily suspended-sediment concentration data. For example, a day-by-day comparison of suspended-sediment concentrations shows an initial increase of ~3-fold during water year 1965 and a decreasing trend during the 15-years that follow (Fig. 5c). It should be noted that the ratios shown in Fig. 5c do not center at unity owing to the overestimation of the Wheatcroft and Borgeld (2000) sediment rating curve for the lower range of river discharge values (cf. Fig. 3c). It should also be noted that this rating curve was specifically generated for the upper range of river discharge conditions (i.e., the solid line in Fig. 3c), so this imbalance is not unexpected or problematic.

Perhaps a better test for suspended-sediment concentrations in the Eel River would focus on the concentrations expected for specific ranges of river discharge, especially the higher values of discharge. The Hirsch et al. (2010) techniques were output for a range of higher discharge values (results from 200, 1000 and 5000 $m^3/s$ shown in Fig. 5d), and when normalized for the average suspended-sediment concentration for each discharge value, these results show similar trends for all discharge rates. For example, all sediment concentrations increased during 1965, which is first identified in 1964 owing to the 3-year window of regression, and concentrations trended downward between 1965 and 1980 (Fig. 5d).

Thus, an examination of the USGS daily sediment discharge records revealed two important trends: (i) large increases in the suspended-sediment concentrations coinciding with water year 1965, and (ii) decreases in concentrations with time after 1965 to levels lower than observed in the pre-1965 records. The decreases in concentrations were such that a stationary sediment rating curve significantly overestimated sediment discharge during the final potion of the 1960–980 time series. Several questions may be asked of these results: (a) Do the downward trending suspended-sediment concentrations continue during the years after 1980? and

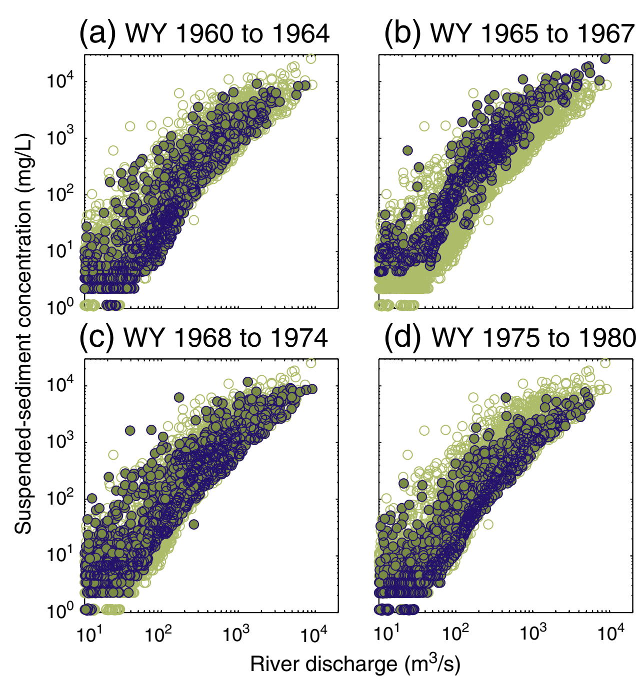


**Fig. 4.** Time-depended trends in the USGS-estimated daily mean concentrations of river suspended-sediment concentrations for the Eel River at Scotia gaging station (USGS 11477000). Each plot shows the complete record (light symbols) and records from selective water years (darker filled symbols). Only data records with discharge in excess of 10 $m^3/s$ are shown to highlight the highest range of river discharge.

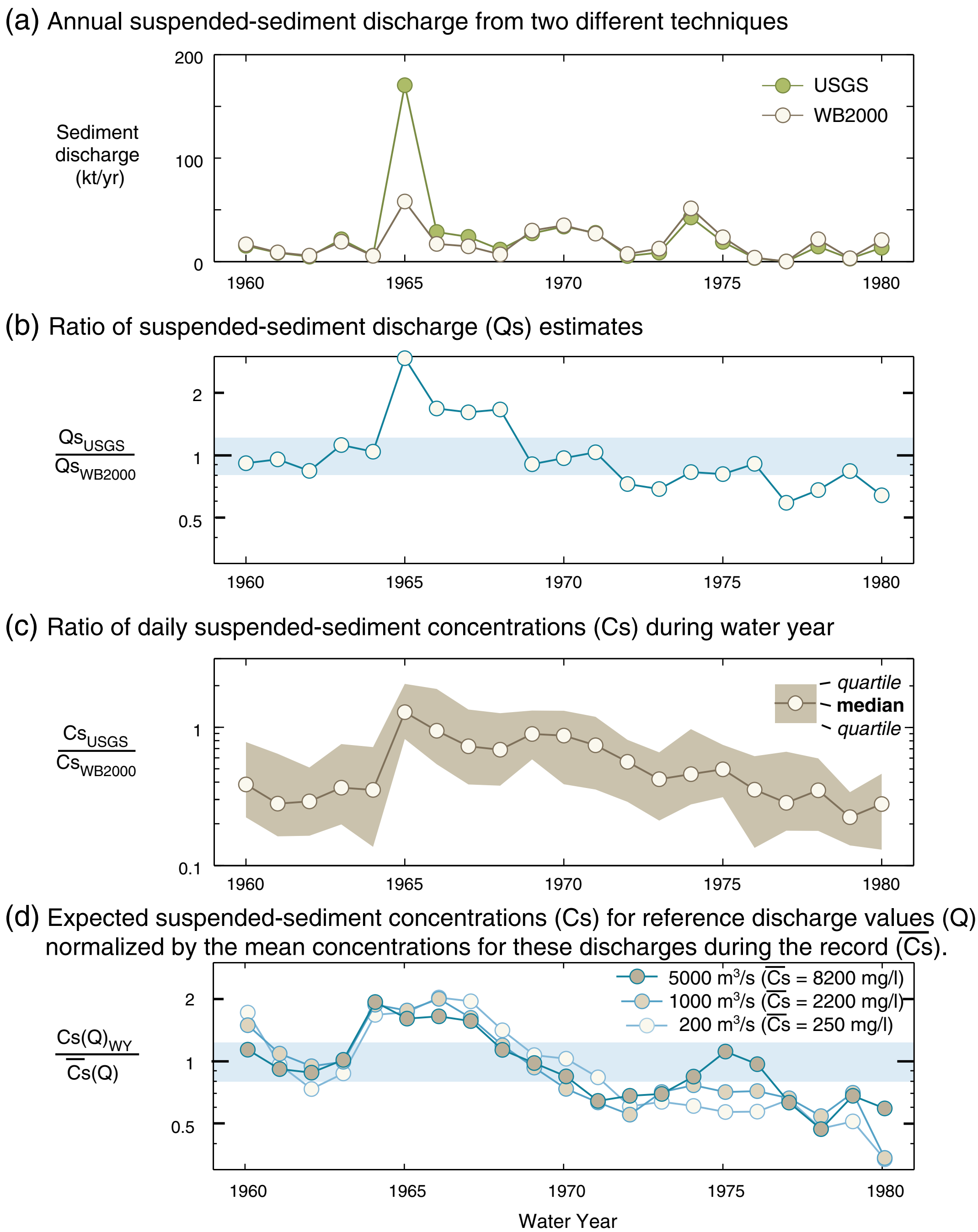


**Fig. 5.** Comparison of suspended-sediment discharge estimates for the Eel River at Scotia gaging station (USGS 11477000) during water years 1960–1980 from two different methods: the USGS techniques that incorporate time-dependent changes in the discharge–sediment concentration relationships and the sediment rating curve of Wheatcroft and Borgeld (2000) "WB2000", which is shown in Fig. 3c. (a) Annual sediment discharge estimates. (b) The ratio between these annual estimates. (c) Comparison of the predicted daily sediment concentrations between the two methods. (d) Expected sediment concentrations for various river discharge values using the USGS daily values and the time-dependent analyses of Hirsch et al. (2010).

(b) How do these trends influence the sediment mass balances developed for marine margin? These questions will be examined in the next two sections.

### 3.2. Sediment discharge trends — post-1980

To evaluate sediment discharge trends after the daily USGS records ceased in 1980, one must consider the field measurements of suspended-sediment concentration (Fig. 2). As noted in the Data and methods section, the USGS field efforts following water year 1980 included more regular summer and low flow sampling for water quality purposes. To limit the potential bias that these samples may introduce, all samples collected during the months of May to September and at discharges less than 10 $m^3/s$ were eliminated from the analyses shown in this section. Furthermore, to focus on the fine-grained sediment fraction relevant to the marine sediment mass balance, only the fine-grained suspended-sediment concentrations (less than 63 μm) were considered. The resulting set of fine-grained suspended-sediment concentrations is shown in Fig. 6. To characterize the overall pattern in these data, the river discharge and sediment concentrations were fit with a LOWESS regression, as noted in Part II of the Supplemental Information, owing to curvature in the log-transformed data. However, similar

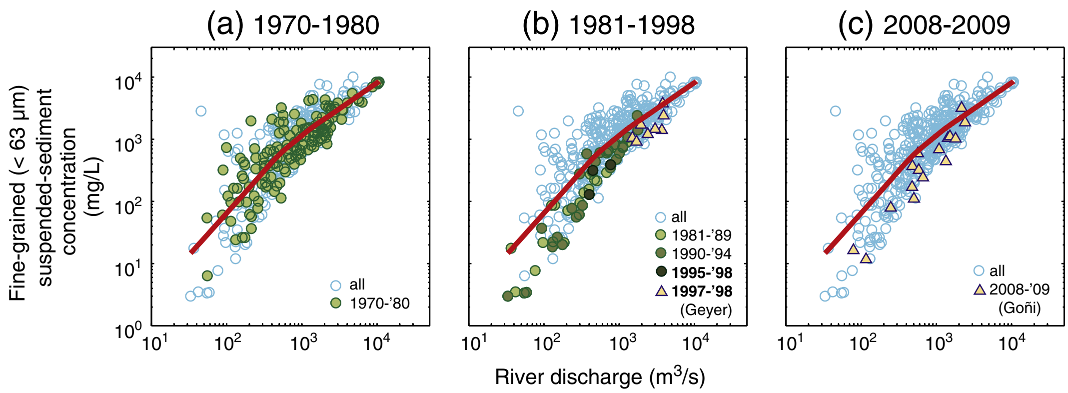


**Fig. 6.** Scatter plots of fine-grained (<63 μm) suspended-sediment concentrations and river discharge from the Eel River at Scotia gaging station (USGS 11477000) highlighting decreases in concentrations during the record. Samples obtained during summer months (June to September) and at low flow (less than 10 $m^3/s$) have been excluded from these analyses. Each subplot includes the complete USGS sample record ("all"; WY1955-1998; unfilled circles) and samples from the specific water years noted (filled symbols). Additional data from Geyer et al. (2000) and Goñi et al. (2013) are shown with triangles. The red line is the LOWESS fit through the complete USGS sample record.

trends to those shown below will be found if power-law regressions are used.

The field measurements allow for a comparison of the data from 1970 to 80, when USGS daily records suggested decreasing trends (see Section 3.1), and data from the post-1980 interval in question. Graphical comparisons reveal that fine-grained suspended-sediment concentrations were generally lower after 1980 than during 1970–80 (Fig. 6). This comparison includes field measurements from Geyer et al. (2000) and Goñi et al. (2013) during high-flow conditions of 1997–2009 (Fig. 6b,c), even though these non-traditional samples should result in systematically *greater* concentrations than those for fine-grained suspended-sediment (cf. Part I of the Supplemental Information). Nevertheless, all concentrations obtained during 1995–97, which is the interval of time for the event-based sediment mass balances, and 95% of the concentrations obtained between 1990 and 2009, plot below the LOWESS regression line developed from the complete data set (Fig. 6).

A more quantitative comparison of the field measurements was conducted by computing the residuals, in $\log_{10}$ units, between the measured sediment concentrations and the LOWESS regression line. These residuals are presented in their linear scales (Fig. 7), which is equivalent to the ratio of these values [i.e., $C_{actual}/C_{lowess} = 10$^$(\log_{10}C_{actual} - \log_{10}C_{lowess})$, where $C$ is concentration] and is consistent with the ratios presented previously in this paper. Residuals from water years 1970–80 were compared with more recent intervals of time, and a consideration for river discharge was included by also evaluating only high flow data (defined here to be 1000 $m^3/s$; Fig. 7b). These data reveal that fine-grained suspended-sediment concentrations continued to drop after 1980. Furthermore, although there is high variability in the residuals that include all data, both analysis techniques show that concentrations during the most recent time intervals were ~50% of the values that would be predicted by the LOWESS curve (Fig. 7). Unfortunately, few high-flow samples were collected during water years 1981–1990 to track the trends during these important conditions and years (Fig. 7b).

Hence, an evaluation of the field measurements suggests that fine-grained suspended-sediment concentrations continued to decrease with respect to river discharge after 1980. These decreases in concentration were consistent with patterns expressed in other rivers of the region (e.g., Klein and Anderson, 2012; Warrick et al., 2013) and the field measurements of the Eel River by Geyer et al. (2000) and Goñi et al. (2013). One implication of these suspended-sediment concentration trends is that a stationary sediment rating curve (whether power-law, LOWESS, or other) would result in an overestimation of the actual sediment discharge during the records after 1980. These topics are examined further in the next section.

### *3.3. Sediment discharge estimates — high flow events of 1995–97*

To estimate fine-grained sediment discharge during the three high flow events of 1995–97, sediment concentrations were estimated for each 15-min discharge value using the LOWESS rating curve shown in Fig. 6. Because this regression overpredicted concentrations during years of interest (see Section 3.2) a correction factor of 0.553, equivalent to the mean ratio between concentrations during 1994–98 and those predicted by the regression for high flow rate samples (i.e., those greater than 1000 $m^3/s$), was multiplied to all concentration estimates. However, it is noted that this correction factor varied little if rates of discharge and years of computation were allowed to vary. The range of uncertainty in this correction factor was 0.391–0.782 as calculated by the standard deviation of the log-transformed residuals, and this uncertainty was applied to the sediment discharge calculations as noted in the Data and methods section. It is noted that the upper range of the correction factor exceeded the value of ~ 0.7 that occurred at the end of the 1960-80 daily data (cf. Fig. 5b). Lastly, a bias correction factor of 1.069

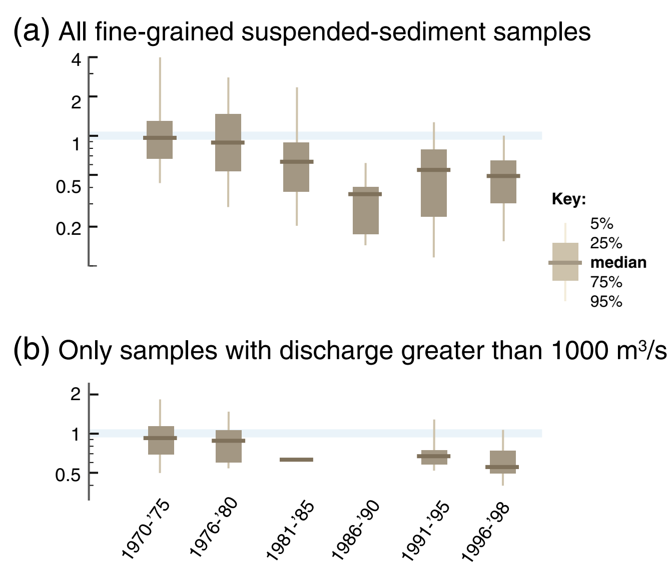


**Fig. 7.** Trends of the Eel River at Scotia fine-grained suspended-sediment concentration residuals about the LOWESS regression line shown for both (a) all samples and (b) only samples obtained during high flow. A comparison is made between the 1970 and '80 samples, which are the first symbols on the lefthand side, and samples taken within 5-year intervals of time after 1980. Percentiles of all residuals are shown with box and whiskers.

was included in these calculations because the LOWESS was performed on log-transformed data.

Water and sediment discharge during the three high flow events of 1995–97 exhibited peak intervals of only hours to days (Fig. 8). The events of 1995 had two distinct peak flows separated by about a week (Fig. 8a,b), whereas the 1997 event had a broader, 3-day peak in high flow (Fig. 8c). These patterns in river flow translated into pulsed sediment discharge the majority of which occurred during a span of only 2–4 days for each event (Fig. 8, bottom panels). Cumulative fine-grained sediment discharge during the three events of 1995–97 ranged from 5.8 to 14.6 Mt, with a total uncertainty of 4.1 Mt to 20.4 Mt (Fig. 8; Table 3). These revised estimates were only 40–50% of the values previously provided by Wheatcroft and Borgeld (2000) as detailed in Table 3.

The revised estimates of the fine-grained sediment discharged by the Eel River during 1995–97 were much closer than the previous estimates to the masses deposited on the continental shelf (Fig. 9). For example, previous estimates of sediment discharge by Wheatcroft and Borgeld (2000) ranged between ~4 and 6 times the rates of shelf flood sedimentation (Fig. 9). The revised estimates were consistently ~2-times the rates of shelf flood sedimentation (Fig. 9). The range of uncertainty in the revised ratios was 1.5 to 3 (Fig. 9). The revised ratios of river sediment discharge to shelf sedimentation are fairly constant across the three events sampled, even though the mass of sediment discharged during these events varied by a factor of three (Fig. 9; Table 3). Thus, the revised sediment discharge estimates computed here suggest that ~50% (uncertainly range = 33–67%) of the river fine-grained sediment was deposited on the adjacent continental shelf during high flow events of 1995–97.

### *3.4. Sediment discharge estimates — 20th century*

Attempting to estimate suspended-sediment discharge over the 20th century is much more challenging than the event-based calculations described in Section 3.3 owing to the general lack of data in the first half of the century (Fig. 2). Yet, with examination of available data and observations, assumptions can be made about the general rates and trends of sediment discharge.

For example, sediment discharge from the Eel River and the surrounding watersheds during the 20th century has been described as being strongly influenced by both infrequent, high flow events and the wide-spread road building and vegetation clearing from mechanized logging during the middle of the century (e.g., Kelsey, 1980; Best, 1995; Best et al., 1995; Nolan and Janda, 1995; Madej and Ozaki, 1996; Sommerfield et al., 2002; Leithold et al., 2005; Madej and Ozaki, 2009; Klein and Anderson, 2012; Madej et al., 2012). The most important high flow event occurred in December 1964 when record peak flow occurred during some of the most intensive logging in the region (Fig. 10a,b). The coincidence of high flow and intensive land use conditions dramatically changed the patterns of suspended-sediment discharge in the Eel River as shown in Section 3.1 and by many other investigators (e.g., Kelsey, 1980; Lisle, 1982; Madej and Ozaki, 1996; Klein and Anderson, 2012; Madej et al., 2012). However, there is also hydrologic and geomorphic evidence that high flows during water year 1955 (Fig. 10a,b) caused increases in landscape sediment supply and river sediment discharge, albeit not to the extent observed during 1965 (Waananen et al., 1971; Kelsey, 1980; Madej and Ozaki, 2009). Unfortunately, no suspended-sediment data were collected from the Eel River – or any other comparable river in the region – before or during the 1955 event to characterize the magnitude of its effect on suspended-sediment concentrations (cf. Warrick et al., 2013). Important information does exist, however, in the marine sediment of the Eel River continental shelf, which exhibited substantial increases in the rates of sedimentation (Fig. 10c), greater preservation of flood layers, decreases of sediment grain-size, and a fundamental shift in the types and ages of terrestrial organic matter stored within these sediments at ca. 1955 (Sommerfield et al., 2002; Leithold et al., 2005; Sommerfield and Wheatcroft, 2007). The coincidence of these conditions with the 1955 flood is suggestive of measurable increases in the rates and characteristics of sediment

**Table 3**
Comparison of fine-grained (less than 0.063 mm) suspended-sediment discharge estimates from the Eel River.

| Event date | Estimates of cumulative fine-grained suspended sediment discharge (Mt) | |
|---|---|---|
| | Four methods employed by WB2000[a] (Mt) | This study[b] (Mt) |
| January 1995 | 24.6 (21.8–28.7) | 12.1 (8.5–17.1) |
| March 1995 | 12.3 (10.4–14.7) | 5.8 (4.1–8.1) |
| January 1997 | 36.6 (29.4–45.3) | 14.6 (10.2–20.4) |

[a] WB2000 = Wheatcroft and Borgeld (2000), reported as the mean value (range in reported values shown in parentheses).
[b] Results reported as best estimate with the standard error in the estimate in parentheses.

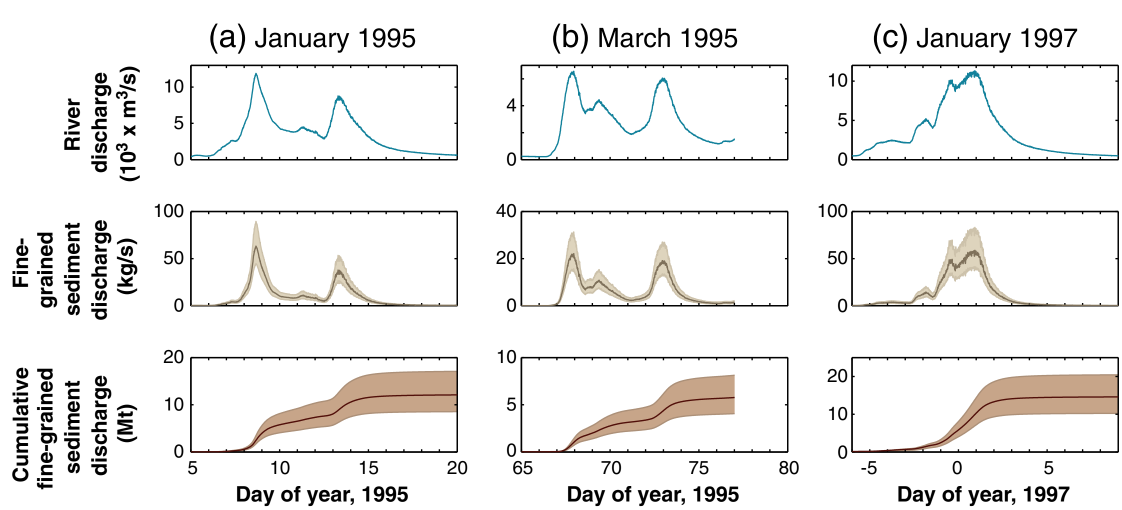


**Fig. 8.** Water and fine-grained (<63 μm) suspended-sediment discharge from the Eel River watershed during three high flows assessed by Wheatcroft and Borgeld (2000). The upper row of figures shows total instantaneous river discharge from the Eel River. The middle row shows computed instantaneous suspended-sediment discharge using the LOWESS rating curve in Fig. 6 with correction for time dependence. The lower row of figures shows cumulative fine-grained suspended-sediment discharge during each flow event. The standard errors of these estimates are shown with shading. Note that the vertical scales are different for each event.

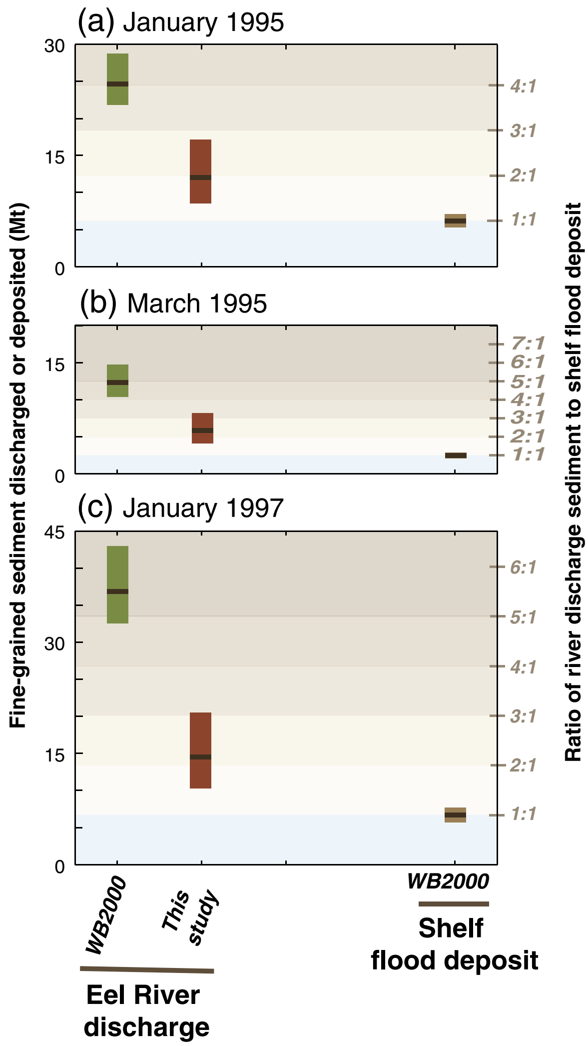


**Fig. 9.** Comparison of the Eel River source-to-sink fine-grained (less than 0.063 mm) sediment budgets for three events of WY1995-97. River suspended-sediment discharge estimates include the four methods employed by Wheatcroft and Borgeld (2000) that do not account for time dependence in the USGS river data ("WB2000") and the revised estimates calculated here. Shelf flood deposit masses from Wheatcroft and Borgeld (2000). Shading shows range of values reported in Table 3 and the 15% reported uncertainty in sediment deposit masses reported by Wheatcroft and Borgeld (2000).

discharge from the Eel River, perhaps not as great as during water year 1965, but large enough to modify the rate and style of marine deposition.

How can these observations be integrated into a model of sediment discharge to the Eel River coastal margin? First, from the results presented in Sections 3.1 to 3.3 it should be acknowledged that an estimation technique should not use a sediment rating curve that is stationary with time. Second, a sediment discharge budget should incorporate both the increases in sediment output during water years 1955 and 1965 and the decay of these effects with time (cf. Fig. 5; Hicks and Basher, 2008). Third, a model must make assumptions about the relative rate of sediment discharge during the first half of the 20th century under the knowledge that (a) river discharge events were measurably lower during the first half of the century than the second half (Fig. 10a), and (b) land clearing during the first half of the century was considerably less than during the second half (Fig. 10b; Best, 1995; Best et al., 1995; Nolan and Janda, 1995).

To facilitate these requirements, several assumptions were made. First, it was assumed that the overall pattern between river discharge and fine-grained suspended-sediment discharge could be explained by a sediment rating curve with time dependence. Second, it was assumed that the USGS daily data best characterized sediment discharge during water years 1960–1980. Third, it was assumed that a fine-grained suspended-sediment rating curve – with time-dependent corrections – was the best manner to estimate sediment discharge for years outside the range of the USGS daily data. Fourth, it was assumed that the effects of the 1955 and 1965 events on sediment discharge could be characterized by initial rises in sediment rating curves and exponential decay toward long-term levels (Fig. 5; Fig. 10d,e; Hicks and Basher, 2008). Fifth, it was assumed that the most recent data from the Eel River (Figs. 6, 7 and 10) could serve as surrogates for the pre-1955 sediment discharge when hydrologic and land use conditions were more moderate than during the middle of the 20th century. That is, it was assumed that the pre-1955 suspended-sediment rating curve was similar to that during the late 20th century.

Combining these assumptions resulted in time-dependent rating curve correction factors shown in Fig. 11a. Included in these factors are: (a) pre-1955 conditions that were assumed to be similar to the late 20th and early 21st century data (cf. Fig. 6), and (b) an exponential decay in the effects of the 1965 event based on high flow (greater than

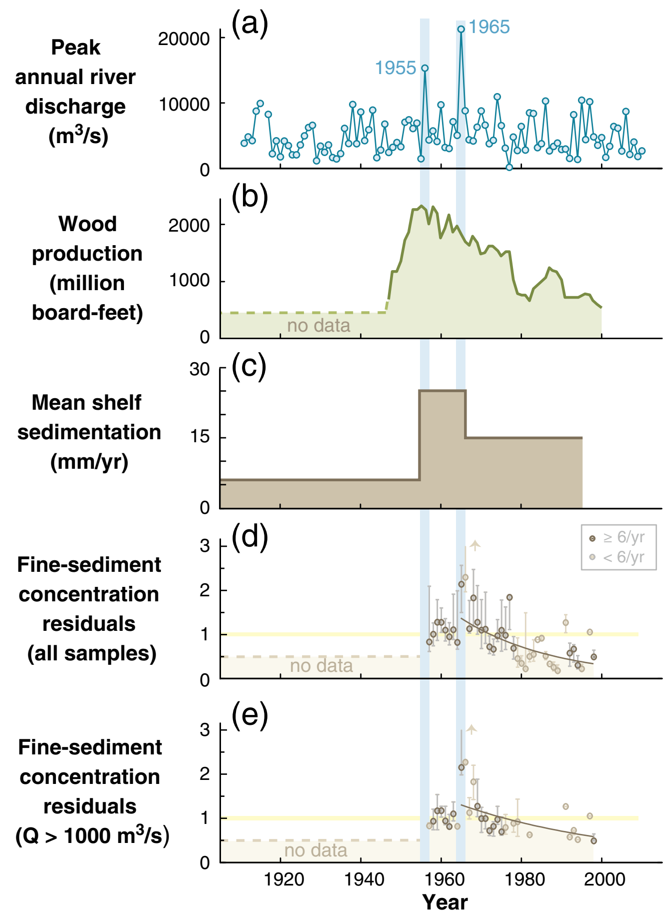


**Fig. 10.** Twentieth-century hydrologic, land use, marine sedimentation, and suspended-sediment discharge behavior of the Eel River. (a) Annual peak discharge at the USGS Scotia gaging station highlighting the two events of record during the 1955 and 1965 water years (vertical bars). (b) Logging rates from Humboldt and Mendocino Counties, California (after Leithold et al., 2005). (c) Mean sedimentation rate on the continental shelf from cores presented in Sommerfield et al. (2002). (d) and (e) fine grained (<63 μm) suspended-sediment concentration residuals about the LOWESS-derived function shown in Fig. 6, shown as the annual median (symbol) and annual percentiles (error bars). Water years with higher sampling rates (greater than 6 samples per year) are highlighted with darker symbols. Least-squares fit exponential functions through the complete post-1964 data are shown with lines. All samples are shown in (d), and only samples obtained during discharge in excess of 1000 $m^3/s$ are shown in (e).

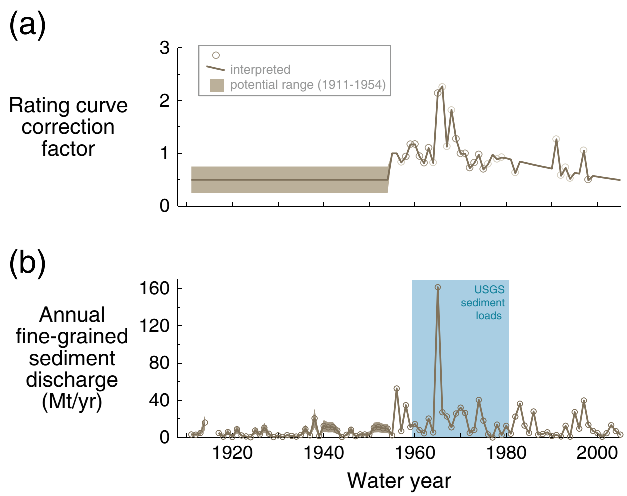


**Fig. 11.** Fine-grained suspended-sediment discharge to the Eel River coastal margin from the combined Eel and Mad Rivers. (a) Annual correction factors for the LOWESS rating curve from USGS fine-grained sediment concentrations used to estimate sediment discharge shown in (b). The shaded region in (b) shows were USGS records were used in lieu of the LOWESS techniques.

1000 $m^3$/s) measurements of suspended-sediment concentrations (cf. Fig. 10e). The largest uncertainty in these correction factors exists for the pre-1955 values assumed to be 0.5, and as such these factors are assumed to range between 0.25 and 0.75 (Fig. 11a).

Using this framework, annual fine-grained sediment discharge to the Eel River margin during 1911–2000 was estimated using Eq. (1), the daily discharge values and a bias correction factor of 1.069. Fine-grained sediment discharge ranged between less than 0.02 Mt and over 160 Mt (Fig. 11b). The greatest annual sediment discharge occurred in water year 1965, and this single year represented over 15% of the total sediment discharge for the 88 years of record. Thus, fine-grained sediment discharge can be summarized as having strong time-dependence that included years with exceptional sediment discharge (e.g., water years 1955 and 1965) and multi-year droughts with comparatively little sediment discharge (e.g., water years 1929–1935 and 1987–1992; Fig. 11b).

Average fine-grained sediment discharge for water years 1911–2000 was estimated to be 11.9 Mt/yr, which was 63% of the previous estimate of 19 Mt/yr computed with a time-stationary sediment rating curve (Table 4). This suggests that the previous values may have been overestimated by a factor of ~1.6. A comparison of the revised fine-grained sediment discharge values and the 20th century rates of marine sedimentation is also presented in Table 4. The revised sediment discharge values suggest that roughly half (48%, or ~5.7 Mt/yr) of the total fine-grained sediment discharge was deposited on the continental shelf during the 20th century (Table 4). This contrasts with previous estimates that only ~30% of the river fine-grained sediment was deposited on the continental shelf (Table 4). Perhaps the greatest difference between the previous and revised sediment budgets is the amount of sediment that could not be accounted for. In previous budgets, the amount of fine-grained sediment that remained unaccounted was ~38% of the total sediment budget; the revised budget suggests that only ~1% of the sediment remained unaccounted for (Table 4).

**Table 4**
Comparison of fine-grained (less than 63 μm) suspended-sediment discharge and margin-wide sediment budget for the Eel River study area over the ~100 yr time-scales relevant to the $^{210}$Pb and $^{137}$Cs sediment mass balances of Sommerfield et al. (2007).

| | Calculations of Sommerfield et al. (2007) | This study |
|---|---|---|
| Average annual fine-grained river sediment discharge (Mt/yr) | 19.0 | 11.9 (*10.6–13.2*) |
| Portion of fine-grained sediment budget deposited upon[a] | | |
| Continental shelf (%) | 30% | 48% |
| Slope (%) | 20% | 32% |
| Canyon (%) | 12% | 19% |
| Unaccounted (%) | ~38% | ~1% |

[a] Sediment mass balance based on conversion of the Sommerfield et al. (2007) sediment budget shown in the first column into average annual deposition rates in Mt/yr in the three primary marine zones (shelf, slope and canyon).

Further details of the source-to-sink fine-grained sediment budgets are shown graphically in Fig. 12. Approximately one-third of the total fine-grained sediment deposited on the continental shelf occurred on the inner shelf, which has water depths less than 50 m and is dominated by sandy sediment; the remaining two-thirds of the sediment occurred on the mid- to outer shelf, which has water depths of 50 to 110 m and is dominated by muddy sediment (Crockett and Nittrouer, 2004; Sommerfield et al., 2007). The estimated mass of fine-grained sediment deposition on the slope (~3.8 Mt/yr) is approximately the same magnitude as the mass deposited on the mid- to outer shelf (Alexander and Simoneau, 1999; Sommerfield et al., 2007; Fig. 12). Sediment deposition in the Eel Canyon, which is immediately south of the mid-shelf flood sediment deposits, has been noted to be rapid following river discharge events, although sediment failures that occur with approximately decadal frequencies are suggested to redistribute much of this sediment mass down canyon (Mullenbach et al., 2004; Mullenbach and Nittrouer, 2006). Thus, the sediment budget presented here utilizes a total sedimentation rate of 2.3 Mt/yr in the Eel Canyon, for which an estimated 20% remains in the upper canyon and is accounted for in $^{210}$Pb inventories, and the remaining 80% is transported far down canyon beyond the region sampled by Mullenbach and Nittrouer (2006; Fig. 12). Thus, in previous sediment budgets of Sommerfield et al. (2007), ~7.2 Mt/yr of fine-grained sediment was unaccounted for and its location unknown (Fig. 12). The revised sediment budgets provided here suggest that negligible sediment remains unaccounted for (Fig. 12).

## 4. Discussion

### *4.1. Differences in estimates of river sediment discharge*

It is useful to examine why revised estimates of river sediment discharge presented here differed with previous estimates. Revised estimates of sediment discharge during high flow events of 1995–97 were ~50% of the mean values reported by Wheatcroft and Borgeld (2000) (Table 3), and the revised estimates for water years 1911–2000 were ~63% of the mean values reported by Sommerfield et al. (2007) (Table 4). The primary cause of these differences is inclusion of time dependencies in the sediment rating curve of the present study. For example, the LOWESS sediment rating curve was corrected by a factor of 0.553 for the 1995–97 events, resulting in estimates that were 40–50% of the previously reported values. Thus the correction factor, which incorporates the strong decreases in the suspended-sediment concentrations with time, accounts for the majority of the differences in the two results. Thus, any differences between the modified power-law rating curves used by Wheatcroft and Borgeld (2000) and the LOWESS rating curve used here are secondary to the time-dependent trends. Similarly, the revised 20th century sediment budgets developed here differ from those constructed by Sommerfield and Nittrouer (1999) primarily owing to the inclusion of time-dependent correction factors to incorporate the observed and hypothesized trends in sediment discharge properties of the Eel River.

It must be emphasized that the differences in these sediment discharge estimates were not the result of poorly chosen techniques by

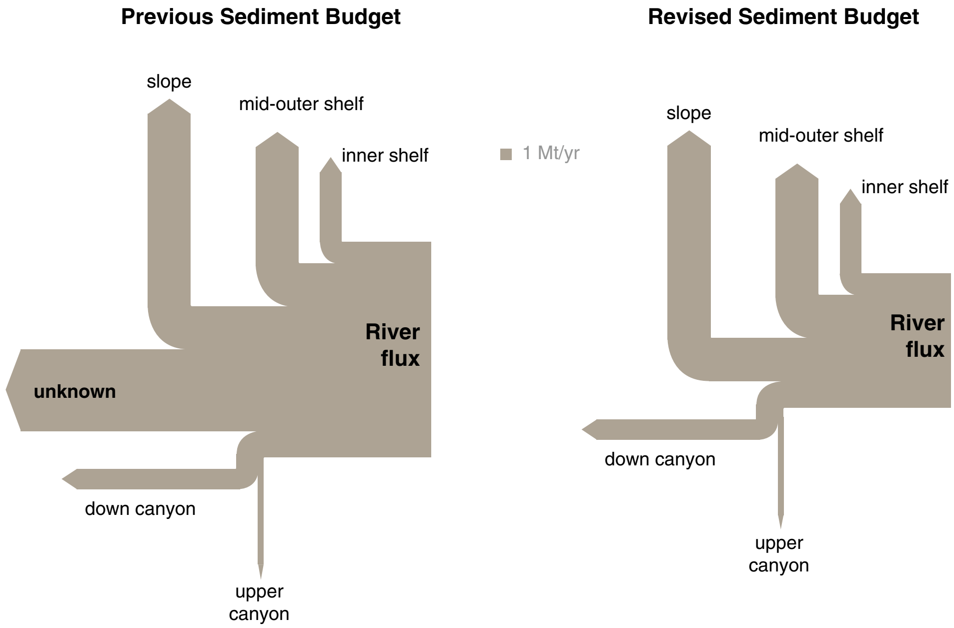


**Fig. 12.** 20th century fine-grained sediment budgets for the Eel River coastal margin highlighting differences between previous estimates synthesized by Sommerfield et al. (2007) and revised estimates shown here. The thickness of the arrows scale with mean annual sediment flux to regions of the margin over the 20th century. The primary difference is that the previous budget estimated greater river sediment discharge (flux), which resulted in a substantial portion of the sediment attributed to "unknown" regions. The revised budget is based on the sediment discharge from the combined Eel and Mad Rivers using the techniques provided in this study, and it does not have sediment attributed to "unknown" regions.

previous researchers. On the contrary, previous researchers followed fairly standard methods of assuming sediment rating curves are stationary with time, consistent with numerous well accepted studies of the region and similar watersheds (e.g., Brownlie and Taylor, 1981; Inman and Jenkins, 1999; Hicks et al., 2000; Willis and Griggs, 2003; Farnsworth and Warrick, 2008; Warrick and Mertes, 2009; Andrews and Antweiler, 2012). Yet, techniques that assume stationary rating curves are not useful if the relationships between river discharge and suspended-sediment concentrations exhibit time-dependent trends. Portertield (1972) warned about these time-dependent changes when calculating sediment discharge, and several researchers (e.g., Anderson, 1970; Brown, 1973; Knott, 1974; Kelsey, 1980) reported time-dependent trends in the Eel River and other regional watersheds, albeit decades ago. Thus, there is perhaps a more general need to test the assumptions of stationary sediment rating curves in future studies because while these assumptions have become the norm for many – including the present author (cf. Farnsworth and Warrick, 2008; Warrick and Mertes, 2009) – there is ample evidence that hydrologic systems shouldn't be stationary, especially with the past, present and pending human changes to these systems and the inherent variability in climate (e.g., Hicks, and Basher, 2008; Milly et al., 2008).

### *4.2. Implications of the revised sediment budgets*

Revised analyses presented here suggest that previous source-to-sink sediment budgets for the Eel River margin overestimated river inputs to the margin (Tables 3 and 4). The revised sediment discharge budgets suggest that ~50% of the discharged river fine-grained sediment was deposited and stored on the continental shelf during both the initial weeks following discharge events and over the longer, decadal time scales (Figs. 9 and 12). These results contrast with previous estimates that suggest only ~25% of the river fine-grained sediment accumulated on the shelf (Wheatcroft et al., 1997; Sommerfield and Nittrouer, 1999; Wheatcroft and Borgeld, 2000; Hill et al., 2007; Sommerfield et al., 2007).

Not only are the revised mass balances of fine-grained sediment important in accounting of sediment across this coastal margin, but they also help constrain patterns and processes of sediment dispersal. For example, Hill et al. (2007, p. 86–92) provide a summary of the potential fate of the unaccounted for, or missing, sediment in the previous budgets. Studies that have attempted to better understand this missing sediment have utilized numerical modeling of sediment transport (e.g., Scully et al., 2003; Harris et al., 2005), monitoring of sediment transport off of the continental shelf in the farfield and Eel Canyon regions (e.g., Puig et al., 2003; McPhee-Shaw et al., 2004; Puig et al., 2004), and sediment coring (e.g., Wheatcroft and Sommerfield, 2005; Mulllenbach and Nittrouer, 2006). The leading hypothesis from this body of work has been that the Eel River margin is significantly different from the other studied coastal systems along the west coast of North America because it has a higher rate of sediment export from the shelf (thereby resulting in the unaccounted for sediment). If correct, this hypothesis implies that the Eel River margin may be unique owing to its sediment delivery timing, wave climate, and/or shelf geometry (Wheatcroft and Sommerfield, 2005; Sommerfield et al., 2007). Here I offer another explanation, that there may be very little "missing" sediment in the budget (cf. Fig. 12; Table 4), and that the Eel River margin is therefore quite similar to previously studied river margin systems (e.g., the Washington, Russian River, and Santa Cruz shelves; cf. Sommerfield et al., 2007) that retain most of their river-derived fine-grained sediment on the adjacent continental shelf.

## 5. Conclusions

A reexamination of the river sediment discharge data from the Eel River suggests that rates of fine-grained suspended-sediment discharge varied strongly with time and included increases in concentrations during water year 1965 and substantial decreases with time afterward. Including these trends in calculations of fine-grained sediment discharge to the Eel River coastal margin results in substantially different margin-wide sediment budgets than reported previously. The revised budgets presented here suggest that approximately half of the river fine-grained sediment discharge has accumulated in the continental shelf flood deposits over both event and century scales. Not only does this alter the source-to-sink sediment budget per se, but it also necessitates a reexamination of sediment export hypotheses based on these previous budgets. A revised hypothesis is presented here that suggests that the Eel River margin is similar to other river-dominated shelf systems in the region that store most of their discharged fine-grained sediment on the adjacent shelf.

Although river sediment discharge measurements are critical for studies of sediment dispersal in coastal margins, sustained suspended-sediment data collection by agencies such as the USGS for rivers like the Eel is becoming rarer with time (e.g., Warrick et al., 2013). With this in mind, there are a number of surrogate monitoring techniques that, when combined with traditional flow-weighted suspended sediment sampling, can result in accurate estimates of sediment discharge (e.g., Gray and Gartner, 2009). Furthermore, as shown here non-traditional sampling techniques, such as those employed by Geyer et al. (2000) and Goñi et al. (2013) can provide useful information about fine-grained suspended sediment if used carefully. With continued reductions in river monitoring programs, future source-to-sink studies along river-dominated margins will be challenged to develop river sediment discharge estimates with the limited data that exist and may need to employ surrogate sampling techniques. As shown here, one must be especially careful because suspended-sediment concentrations – and the sediment rating curves based on these data – may exhibit significant trends in time.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.margeo.2014.03.008.

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