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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.

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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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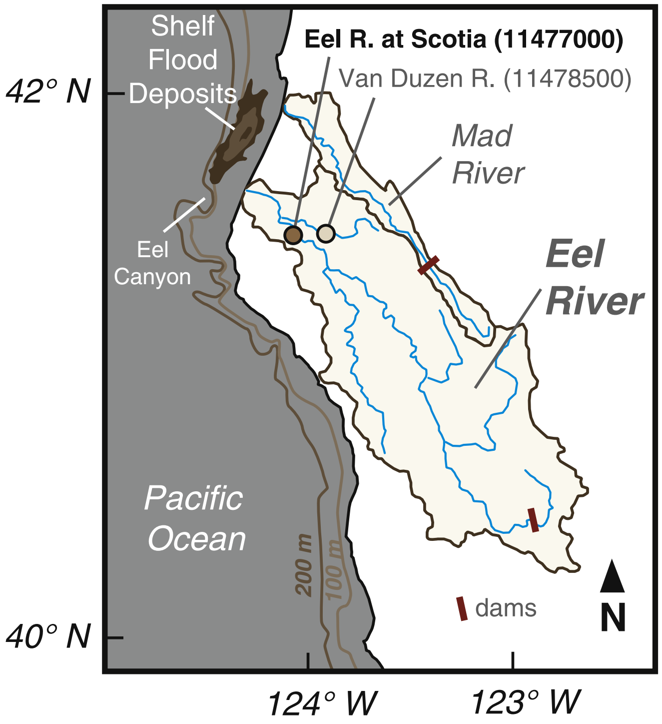

Fig. 1. Map of the Eel River study area showing the watershed, USGS river sampling stations (filled symbols), and flood sediment deposits on the continental shelf (shading) as defined by sedimentation during the 1995–1997 water years by Wheatcroft and Borgeld (2000).

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,