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"The offshore export of sand during exceptional discharge from California rivers"

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CALCULATION OF RIVER SEDIMENT DISCHARGE AND GRAIN SIZE DISTRIBUTION

The sediment discharge from the San Lorenzo and Santa Clara Rivers were estimated using the data and techniques of Hicks and Inman (1987) and Barnard and Warrick (2010). These techniques included a suspended-sediment rating curves derived from USGS suspended-sediment samples, an estimation of bedload discharge, grain-size distributions from suspended and bedload sediment samples, and river discharge information. For both rivers, the sediment discharge calculations were conducted for the last USGS surface water stations on each river: USGS 11160500 (San Lorenzo River at Big Trees) and USGS 11114000 (Santa Clara River at Montalvo).

The suspended-sediment rating curves for the San Lorenzo River is discussed in Hicks and Inman (1987), and the suspended-sediment rating curves for the Santa Clara River is provided by Brownlie and Taylor (1981) as described in Barnard and Warrick (2010). To estimate the fraction of this suspended-sediment discharge in coarse (sand and gravel) fractions, we utilized the grain-size distribution data available for suspended-sediment samples of each USGS station. Because the vast majority of coarse sediment discharge from California rivers occurs within hours of the peak discharge (Warrick and Milliman, 2003), we evaluated the sediment grain-size distributions from samples taken at high discharge. It was found that no discharge-dependence for suspended-sediment grain size distributions occurred above 10 and 100 m^3/s for the San Lorenzo and Santa Clara River, respectively. Eliminating samples taken below these discharge thresholds resulted in counts of total "high flow" suspended-sediment samples of 50 and 26 for the San Lorenzo and Santa Clara Rivers, respectively (Table DR-1). The average proportion of coarse sediment (i.e., larger than 0.063 mm) in the suspended sediment was found to be 39.8% and 28.9% for the San Lorenzo and Santa Clara Rivers, respectively (Table DR-1). Mean grain-size distributions of the coarse suspended sediment during high flows are provided in Table DR-1.

To calculate the total coarse sediment grain-size distributions, the suspended and bedload data were combined by assuming a 9:1 ratio of suspended:bedload sediment flux by mass, which is commonly utilized for coastal California rivers (Brownlie and Taylor, 1981; Willis and Griggs, 2003). The grain-size distributions of bedload samples were calculated using the discharge thresholds noted above.

This resulted in 24 samples from the San Lorenzo River and only one from the Santa Clara River. Mean coarse grain-size distributions for these bedload samples are listed in Table DR-1. The combination of suspended and bedload sediment grain-size distributions using the ratio noted above is provided in Table 1 of the paper.

To estimate sediment discharge during the hydrologic events highlighted in this paper, the suspended-sediment rating curves were applied to the available USGS river discharge records. For the San Lorenzo River, we utilized the calculations provided by Hicks and Inman (1987). For the Santa Clara River, we utilized the calculations provided by Barnard and Warrick (2010), although we highlight a few details of these calculations below.

Because Santa Clara River gauge was decommissioned at the end of water year 2004, the sediment loads for water year 2005 were estimated using the largest tributary and most important discharge source in the Santa Clara River watershed, Sespe Creek (Warrick and Mertes, 2009). For these estimates, the total suspended sediment flux from Sespe Creek (USGS 11113000 — Sespe Creek near Fillmore) was estimated using the best-fit power-function with mean daily discharge of Sespe Creek (Eqn. 4 in Barnard and Warrick, 2010). The linear regression between annual sand transport from the Santa Clara River and annual suspended sediment transport from Sespe Creek was found to be significant at $r^2 = 0{:}96$ ($n = 30$; Eqn. 5 in Barnard and Warrick, 2010). This relationship then was used with the Sespe Creek average daily discharge records to estimate the annual littoral sand transport from the Santa Clara River during 2005. As noted by Barnard and Warrick (2010), there are large uncertainties (~50%) in these sediment discharge estimates.

MAXIMUM SAND EJECTION DISTANCE CALCULATIONS

Maximum sand ejection distances within hypopycnal plumes were calculated to assess whether hypopycnal processes could explain the observed deposition patterns on the deltas. Throughout these calculations, conservative assumptions were made. These assumptions resulted in computed ejection distances that should be overestimated.

The basic hypopycnal plume model utilized for these calculations utilized the initial river mouth geometry as determined from the pre-event topographic and bathymetric surveys (Hicks and Inman, 1987; Barnard and Warrick, 2010) and aerial photographs of the river mouths taken immediately after the river discharge events. River mouth widths at flood discharge are reported in Table DR-2.

The hypopycnal model assumed no horizontal plume spreading offshore of the river mouth. This made calculations simple, and resulted in particle ejection distances that were farther than expected for a spreading (and, therefore decelerating) plume. The plume calculations also assumed a constant plume thickness, which was determined to be 4 m after the work of Warrick et al. (2004) and Warrick et al. (2007). The across-shore speed (m/s) of the plume was calculated as the ratio of the river discharge rate (m^3/s) to the product of the plume width (m) and the plume thickness (m).

The river discharge rate was chosen to be the maximum measured or inferred rate during the floods. The peak discharge of the Santa Clara River during 2005 was estimated from the relationships between peak discharge rates at the river mouth and at two upstream gaging stations: Sespe Creek (USGS 11113000 — Sespe Creek near Fillmore), Santa Paula Creek (USGS 11113500 — Santa Paula Creek near Santa Paula). Historical peak discharges between these stations and the Santa Clara River mouth station (USGS 11114000) were highly correlated as shown by Warrick (2002) and these tributary peak discharges during 2005 averaged 1.4-times the peak discharges of the previous record flows of 1969. Thus, the peak discharge at the Santa Clara River mouth during 2005 was estimated to be 6500 m^3/s, which is 1.4-times greater than the 1969 peak discharge of 4700 m^3/s.

Vertical settling of sand was modeled with constant settling rates computed with the equations of Ferguson and Church (2004). A grain-size of 0.1 mm was utilized because it was a common mean grain size measured in the Santa Clara River delta at 10 m water depth (see Table 2 of the paper). However, we also provide estimates for ejection distances for a range of sand particle sizes (0.063 to 1 mm). Particle settling assumed constant settling across the entire depth of the plume. While in the plume particles were advected at the computed across-shore plume speed. Particles travelled at zero across-shore speeds once settled below the hypopycnal plume, which ignores the potential return flow commonly observed beneath a hypopycnal plume (another conservative assumption).

The maximum particle ejection distances were equivalent to the total across-shore distance traveled by these modeled sand particles in the plume (i.e., the product of the particle's time in the plume and the across-shore plume speed). The calculations were is insensitive to plume thickness (we used a range of 1-6 m), owing to the linear and inverse relationship between plume thickness and across-shore plume speed. Results of the calculations for 0.1 mm particles are provided in Table DR-2. A comparison between sand grain-size and maximum ejection distance is provided in Figure DR-1.

Uncertainty in these computations occurred from all of the reported variables. The uncertainties in the river mouth widths were approximately 10%. Uncertainties in the discharge measurements were approximately 10% for the San Lorenzo River and 30% for the Santa Clara River. The computations were insensitive to either plume depth or speed, because these variables were inversely related. Thus, the total uncertainties in these results were approximately 20% and 40%, respectively. We note that the computed sand ejection distances were within 4% (Table DR-2), which suggests that they are not significantly different from one another. However, the measured sand ejection distances (850 m and greater than 1400 m) differ by a factor of at least 1.6, which is greater than the worst-case combined uncertainty (60%) in the calculated ejection distances.

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TABLE DR1. GRAIN SIZE CHARACTERISTICS FOR THE RIVERS MODELED.

Grain size class	Size range (mm)	Setting rate†, w_s (mm/s)	Percent of coarse suspended load* (%)		Percent of bedload* (%)	
			San Lorenzo River§	Santa Clara River§	San Lorenzo River§	Santa Clara River§
Very fine sand	0.063-0.125	7	27.1	38.2	1.2	1.0
Fine sand	0.125-0.250	22	29.7	29.3	7.0	11.0
Medium sand	0.25-0.50	51	33.3	17.8	18.8	26.0
Coarse sand	0.5-1.0	98	8.9	4.7	22.6	17.0
Very coarse sand	1-2	160	1.5	1.1	15.6	15.0
Gravel	>2	160#	0.0	0.0	34.4	30.0
Number of samples			***50***	***26***	***24***	***1***

* Mean grain size information calculated from samples during high discharge (greater than 10 and 100 m^3/s for the San Lorenzo and Santa Clara River, respectively).

† Sediment settling rate calculated from the mean particle size in each 1-phi class using the equations of Ferguson and Church (2004).

§ From measurements at USGS surface water stations 11160500 (San Lorenzo River at Big Trees) and 11114000 (Santa Clara River at Montalvo).

TABLE DR2. RIVER MOUTH CHARACTERISTICS FOR THE SAND EJECTION CALCUALTIONS FOR THE TWO RIVER MOUTHS.

	San Lorenzo River	Santa Clara River
Sediment grain size (mm)	0.1	0.1
Sediment settling rate (mm/s)	7.5	7.5
River mouth width (m)	100	800
Peak river discharge (m^3/s)	840	6500
Plume thickness (m)	4	4
Computed plume velocity (m/s)	2.1	2.0
Computed maximum time of particle in plume (s)	400	400
Computed maximum distance of sediment ejection (m)	1120	1080

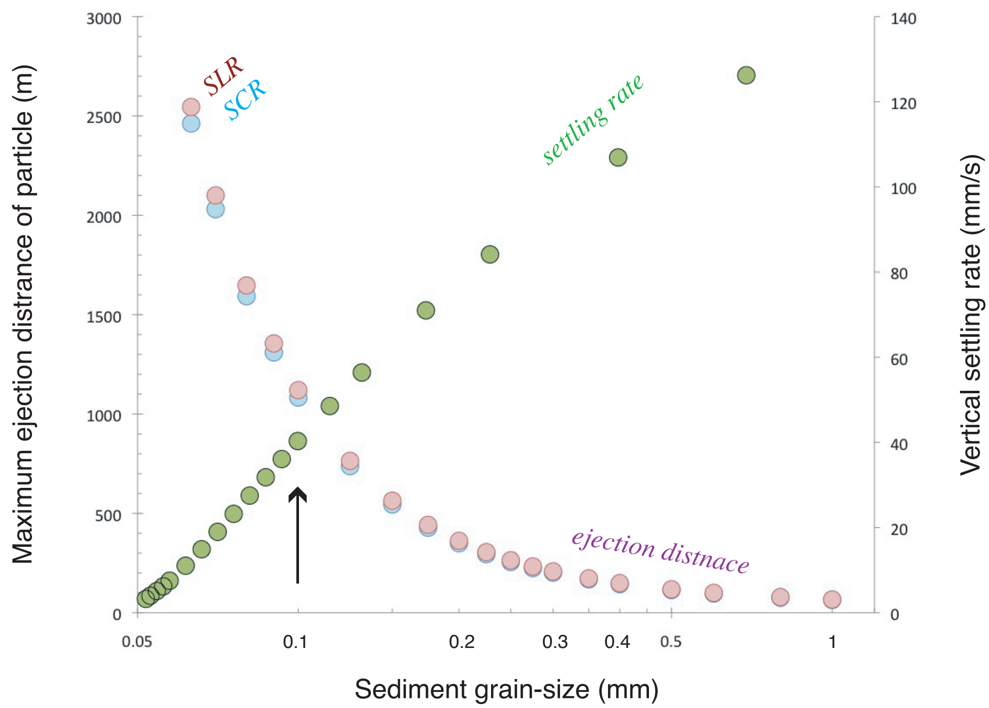

Figure DR-1. The effect of sediment grain-size on the computed maximum particle ejection distance from the river mouth in a hypopycnal plume. Ejection distances are shown for both the San Lorenzo River (red symbols) and the Santa Clara River (blue symbols). For comparison, the verticle settling rates from the equations of Ferguson and Church (2004) are shown with green symbols. An arrow denotes the results for 0.1 mm sand shown in Table DR-2 and discussed in the body of the paper.