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River Floods Under Wetter Antecedent Conditions Deliver Coarser Sediment to the Coast

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Key Points:

- Sand proportion in river flood sediment is significantly greater with wetter antecedent conditions, consistent with more hillslope supply
- Extreme wet years have substantial, years-long influence on coastal morphology
- Future climate likely will enhance coarse fluvial sediment delivery to U.S. west coast

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Increasing hydrologic volatility—more extreme rain, and larger variations between wet and dry years—has become apparent in some regions, but few data exist to determine how intensifying hydrologic extremes affect sedimentary systems. Using uniquely high-resolution records of fluvial suspended sediment and coastal morphology, we quantify sedimentary responses from a steep, 357-km^2 watershed in California under extreme wet and dry hydrologic conditions. In years with multiple 2- to 10-year floods, fluvial sediment coarsened significantly as the wet season progressed, with late-season floods delivering dominantly sand-sized material to the coast. Greater and coarser sediment supply under wetter antecedent conditions affected nearshore geomorphic evolution for 4–5 years. The watershed and coastal changes we documented point to an increasing role of sediment-related hazards (flooding and hillslope erosion) and resources (nearshore accretion) as wet seasons intensify.

Plain Language Summary Some regions are experiencing more extreme rain and a stronger contrast between extreme drought and extreme wet years. Understanding how those extremes affect sediment moving through rivers is important for assessing hazards, risk to ecosystems, and managing resources in rivers and along coastlines where rivers deliver sediment, but not much is known about how river sediment is responding to shifts in hydrologic extremes. We studied river and coastal sediment over more than a decade in the San Lorenzo River area (California coast), including collecting data during extreme wet years and extreme dry years. During extreme wet years when multiple floods occurred, the river started carrying much more sand-sized material, consistent with many landslides dumping new sediment into the river and its tributary creeks. The greater proportion of river sand delivered to the coast late in those wet seasons (in contrast to finer-grained, mostly mud-sized material in non-extreme-wet years) means those extreme wet years have an outsized influence on the sand supply to beaches and other nearshore sediment deposits. The extra sediment from extreme wet years stays in the nearby coastal region for 4–5 years and could help counteract beach losses expected from sea-level rise.

1. Introduction

Landscape responses to greater hydrologic volatility in a warmer climate (Swain et al., 2025) are expected to increase watershed sediment export episodically due to increased supply from hillslope erosion, including slope failures, and greater transport capacity in streamflow responding to heavy rain (East et al., 2022; East & Sankey, 2020; Gariano & Guzzetti, 2016; Jakob & Lambert, 2009; Zhang et al., 2023). Although these responses have been theorized and modeled for multiple regions (Neverman et al., 2023; Sankey et al., 2017; Xie et al., 2024) and analyzed empirically in high mountain Asia (Li et al., 2020, 2021), overall, few data exist to demonstrate how shifts in such processes work. This study examined the influence of rainfall extremes on fluvial sediment delivery from a small, mountainous watershed, and the associated coastal geomorphic impacts in the littoral system near the river mouth. Small, steep basins are collectively the largest source of terrestrial sediment to the ocean (Milliman & Syvitski, 1992); understanding their sedimentary response to extreme hydrologic swings has important implications for fluvial and nearshore hazards, ecosystems, and resource management.

Increased interannual rainfall volatility ("whiplash") has become identifiable over recent decades in California, USA (Swain et al., 2018, 2025; Zamora-Reyes et al., 2022). Recent drought (2012–2015, 2020–2022) and wet years (2017 and 2023, especially) reached new extremes in the modern record (Hatchett et al., 2015; Gershunov et al., 2017; U.S. Drought Monitor, 2025). We examined the sedimentary response to these hydrologic swings in the San Lorenzo River, a 357-km^2 watershed in the Santa Cruz Mountains, central California coast, within the

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"Csb" Mediterranean-type climate zone (warm, dry summers and a cool, wet season from November to March; Beck et al., 2023). The steep (maximum elevation 814 m), rural San Lorenzo River basin remains largely forested despite some legacy effects of 19th-century logging (Chapman et al., 2022). The river flows through gorges with steep walls of mobile regolith and bedrock (sandstone, siltstone, and diorite/granodiorite; Finnegan et al., 2017) and has no mainstem dams or appreciable floodplain sediment storage (only several short alluvial reaches), allowing rapid transmission of environmental signals from the headwaters to the coast (a "reactive" type watershed; Warrick et al., 2023). Fluvial sediment delivery to the California coast occurs primarily during short-duration rainfall-driven floods that carry most of the annual sediment load during just a few days each year, forming the main sediment supply to regional beaches (Best & Griggs, 1991; Hicks & Inman, 1987). The rainy season has become shorter and sharper in recent decades, indicating greater likelihood of intense and extreme rain events (Luković et al., 2021). East et al. (2018) demonstrated that annual fluvial sediment loads from the San Lorenzo River varied 500-fold between extreme dry years and the extreme wet year of 2017, and that anomalously large inputs in wet years appeared key to maintaining beach sediment supply. Here we expand that uniquely high-resolution record of suspended-sediment evolution through 2024, encompassing 21 flows at or above the 2-year flood magnitude. We demonstrate, for the first time, that floods in a steep, mountainous setting carry a significantly greater proportion of sand under wetter antecedent conditions compared to similar-magnitude floods under drier antecedent conditions. Further, we quantify the nearshore geomorphic effects and temporal persistence of the ephemeral subaqueous delta deposits formed during wet years.

2. Data and Methods

Depth-integrated single-vertical 1-liter water samples were collected from a bridge over the San Lorenzo River thalweg immediately above the intertidal zone (Figure 1a) using a winch-operated US D95 sampler. The sampling location is within a leveed, alluvial reach, and the riverbed directly upstream of the sampling location consists of poorly sorted sand and gravel (Dow, 2024). Our sampling targeted discharge above baseflow conditions and especially rain-driven high flows. This analysis focused on 326 samples collected in water years 2016–2024 (i.e., water year 2024 spans 1 October 2023 through 30 September 2024) and one 2010 flood. Samples were analyzed for suspended-sediment concentration (SSC) and the proportion of sand (particles > 0.063 mm) versus silt-and-clay (<0.063 mm). The sampling included three very wet to extreme water years in which "families" of atmospheric-river storms (Fish et al., 2019) brought repeated 2- to ∼10-year floods to the central California coast: water years 2017 (wettest year on record for this region, 188% of normal rainfall, nine floods in nine weeks), 2019 (136% of normal rainfall, six events at or near the 2-year flood magnitude), and 2023 (172% of normal rainfall, five floods; Figures S1 and S2 in Supporting Information S1). We analyzed suspended-sediment data in conjunction with 15-min discharge records from gaging station 11161000 (Figure 1; U.S. Geological Survey, 2025), generating a sediment rating curve that we used (with interpolation between closely spaced samples) to estimate annual loads. We also used the streamflow data to assess antecedent hydrologic conditions, calculating cumulative water-year discharge at the time each sample was collected, as river discharge reflects rainfall and soil-moisture conditions and, at the scale of our study watershed, is expected to reflect actual hydrologic conditions more closely than satellite-derived soil-moisture products (Thomas et al., 2019). We developed supply indices representing the concentrations of sand and silt-plus-clay for discharge conditions during each flood (Supporting Information S1), building on methods developed by Topping et al. (2018).

To measure geomorphic changes in the river-mouth delta and adjacent littoral cell, we surveyed beach topography and nearshore bathymetry biannually over a 2.5-km^2 area using personal watercraft equipped with single-beam echosounders and survey-grade global navigation satellite system (GNSS) receivers; subaerially exposed areas were surveyed on foot using backpack-mounted GNSS receivers. Cross-shore-oriented survey lines were spaced at 50-m intervals. Digital elevation models (DEMs) were produced using linear interpolation between survey lines and used to quantify coastal geomorphic change, including calculations of erosion and deposition volumes.

3. Results

In wet years with multiple 2- to 10-year flood events, the data indicate that floods occurring later in the wet season tended to carry coarser sediment. This pattern is apparent from comparison of floods in the early, middle, and late parts of the winter wet seasons in 2017, 2019, and 2023, as the proportion of sand increased in successive events (Figure 2). Samples late in the falling limb of flood hydrographs late in those wet seasons contained 60%–80% sand, in contrast to 20%–50% at most other times. Coarser sediment late in falling flood hydrographs often

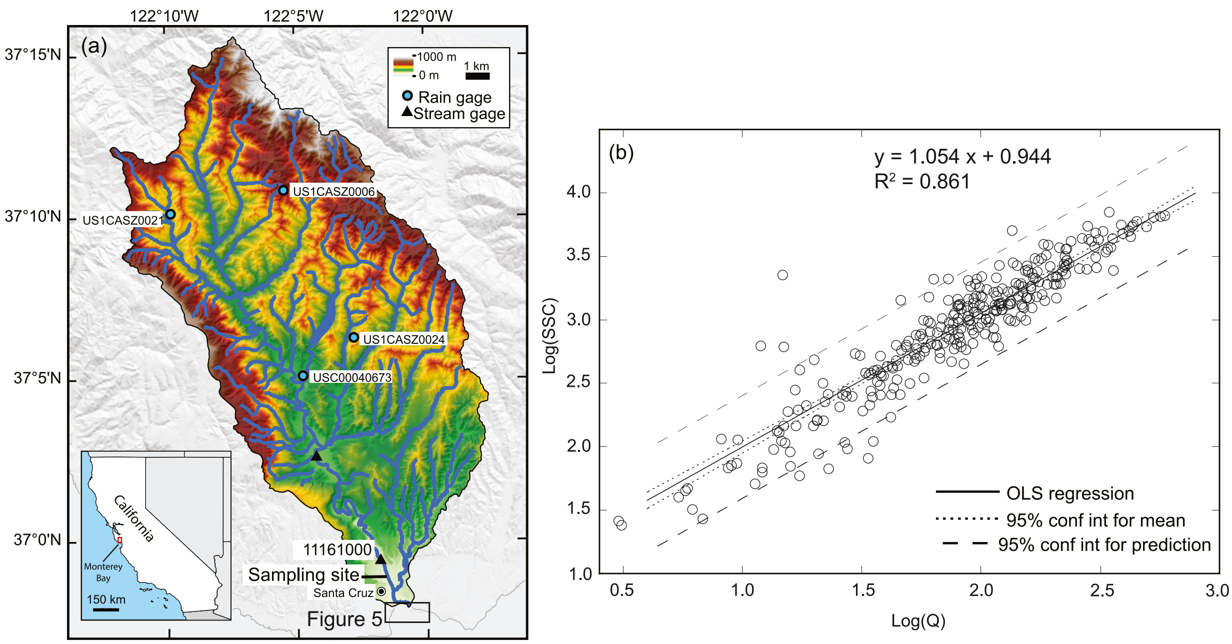

Figure 1. (a) San Lorenzo River watershed, central California coast, which empties into Monterey Bay. Fluvial sediment sampling location is indicated just upstream of river mouth. Locations of rain gages are indicated (National Oceanic and Atmospheric Administration, 2025). (b) Sediment rating curve generated from log-transformed discharge data (Q, m^3/s) and suspended-sediment concentrations (SSC, mg/L). As essentially all of the sediment is siliciclastic, density of 2,650 kg/m^3 can be assumed. OLS, ordinary least squares regression.

accompanied counterclockwise hysteresis in discharge–SSC relationships (Figures 2b and 2g), indicating the arrival of sediment supply traveling more slowly than the water peak (Heidel, 1956; Topping & Wright, 2016). Coarsening was strongly associated with antecedent hydrologic conditions: sand concentrations tended to be higher for a given flow magnitude when the cumulative water-year discharge had been greater (Figure 3). Considering samples collected at discharge >30 m^3/s (values typically associated in this river with rain-driven flow events rather than baseflow), we find a strongly significant positive association between antecedent discharge and the residuals of sand concentration ($p < 10^{-23}$, $r = 0.56$; Figures 3a and 3b). The silt-and-clay fraction of suspended sediment does not show such an association, remaining nearly unchanged with variations in antecedent hydrology ($p = 0.009$, $r = -0.16$; Figures 3c and 3d). The intraseasonal increases in sand concentrations for a given discharge (without corresponding increase in silt and clay) evidently reflect increasing upstream sand supply (Rubin et al., 2020; Topping et al., 2007) and can be represented using sand-supply indices derived from event-based discharge-SSC regressions (Figure 4, Figure S3; Table S1 in Supporting Information S1); higher indices occur when the slope of the discharge-SSC regression line is steeper, indicating higher concentration for a given discharge (cf. Topping et al., 2018).

In extreme wet years, such as 2017 and 2023, that had greater fluvial sediment loads (Figure S2 in Supporting Information S1) and in which late-season floods carried larger proportions of sand (Figures 2–4), the river-mouth delta and nearshore sediment deposits aggraded substantially (Figure 5). In 2017 and 2023, net accretion in this littoral system was 230,000 m^3 and 145,000 m^3, respectively. Assuming a density of 2,650 kg/m^3 and porosity of 40%–45% (Van Rijn, 1993), the new deposits equated to 335,000–366,000 t and 211,000–231,000 t in 2017 and 2023, respectively. This amount of deposition represented two-thirds to three-quarters of the river's annual sediment output when surveyed at the end of the wet season (March). Most of the accretion occurred as subtidal deposition; the 4-m bathymetric contour prograded 200 m seaward in both 2017 and 2023 (Figure S4 in Supporting Information S1). The signal of new fluvial sediment delivery from the 2017 extreme wet year persisted for 4–5 years in the nearshore zone, which is shown by gradual erosion of the winter 2017 deposits until that trend was reversed by arrival of the 2023 flood sediment (Figure 5; minor accretion also occurred in 2019). In years without large fluvial sediment influx, the nearshore geomorphic change is dominated instead by seasonal wave-driven accretion and erosion cycles (Figure 5; e.g., Warrick et al., 2025).

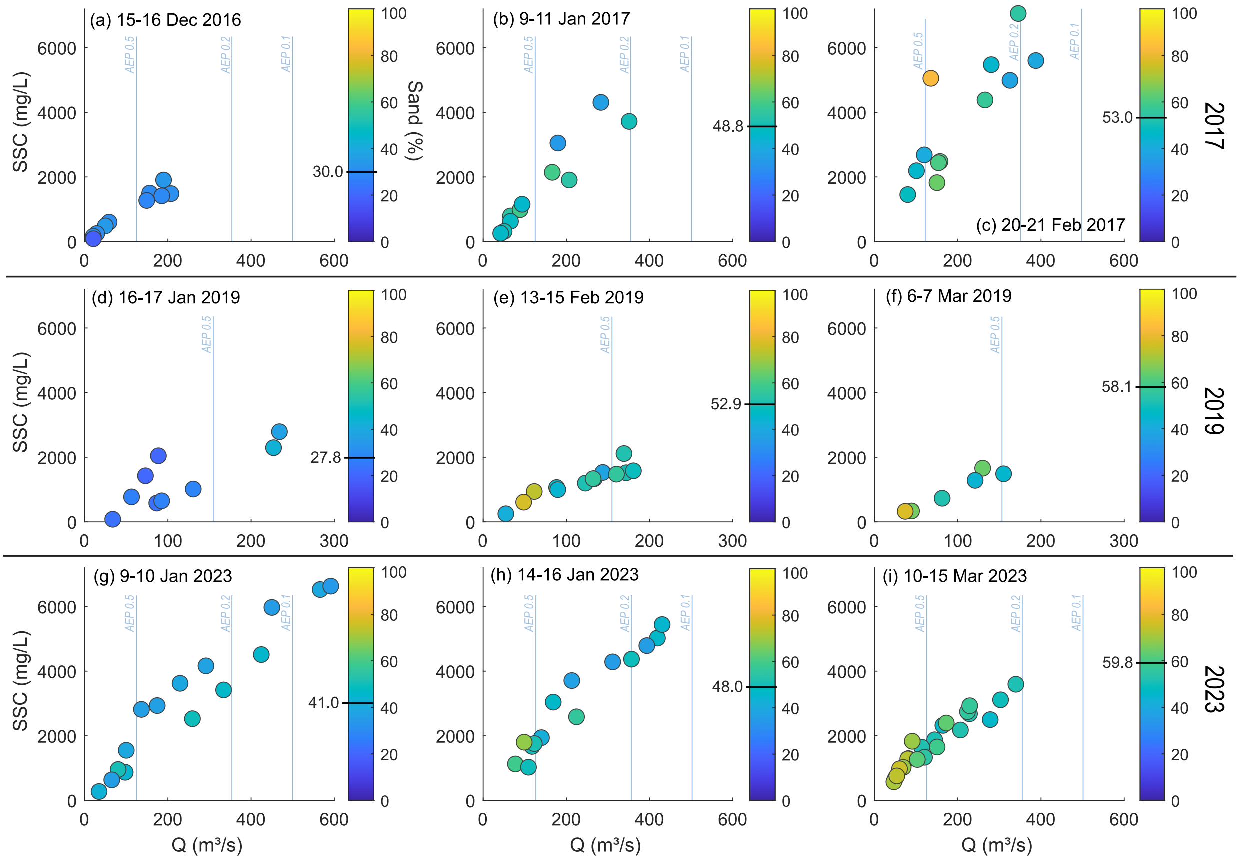

Figure 2. Relationships between river discharge (Q) and suspended-sediment concentration (SSC) for flood events in the early, middle, and late portions of the wet season in three wet years with multiple floods: (a–c) water year 2017 (188% of normal rainfall); (d–f) water year 2019 (136% of normal rainfall); (g–i) water year 2023 (172% of normal rainfall). Blue vertical lines show flow magnitudes associated with annual exceedance probabilities (AEPs) of 0.5, 0.2, and 0.1 (corresponding to 2-, 5-, and 10-year recurrence intervals), respectively. Color bar indicates percentage of sand in SSC samples; black bars through color bars show event-averaged sand content for each flood. In each of the 3 years, late-season floods (c, f, and i) carried greater proportions of sand compared to floods early in the wet season (a, d, and g). Panel (i) combines two back-to-back flood peaks that occurred within 5 days.

4. Discussion and Conclusions

Greater hydrologic variability—more extreme rain, and larger fluctuations between wet and dry years—is widely projected as climate warms (Huang et al., 2020; Swain et al., 2025; U.S. Global Change Research Program, 2023), but few data exist to demonstrate in detail how fluvial and coastal sedimentary systems could respond to these changes. Using a uniquely high-resolution record of fluvial sediment (>320 samples, representing conditions throughout 21 flood events during a decade of extreme hydrologic variations in California) and coastal morphology (more than a decade of biannual surveys), this study quantifies for the first time how fluvial sediment can evolve within extreme wet seasons and between extreme dry and wet years, and how those variations in fluvial sediment delivery influence coastal geomorphic change.

The increase in sand supply during very wet years is inferred to result from hillslope processes releasing more sediment during late-season storms when soils are at or near saturation. Landslides in the San Lorenzo River basin were common during 2017, 2019, and 2023, consistent with multiple storms having rainfall with sufficient intensity and duration (and antecedent moisture) to surpass regional threshold conditions for the onset of landslide and debris-flow activity (Figures S5, and S6 in Supporting Information S1). In addition to shallow landslides and minor debris flows, additional new sediment supply became available through rilling erosion and tree throw as storms destabilized trees in very wet slopes (Figures S6, and S7 in Supporting Information S1); bank erosion was presumably not a major sediment source as alluvial riverbanks are rare in this steep, confined river channel. New sand supply can reach the lowermost river in just hours, given the close temporal correspondence between suspended-sediment coarsening and local reporting of landslides (East et al., 2018); this rapid response is

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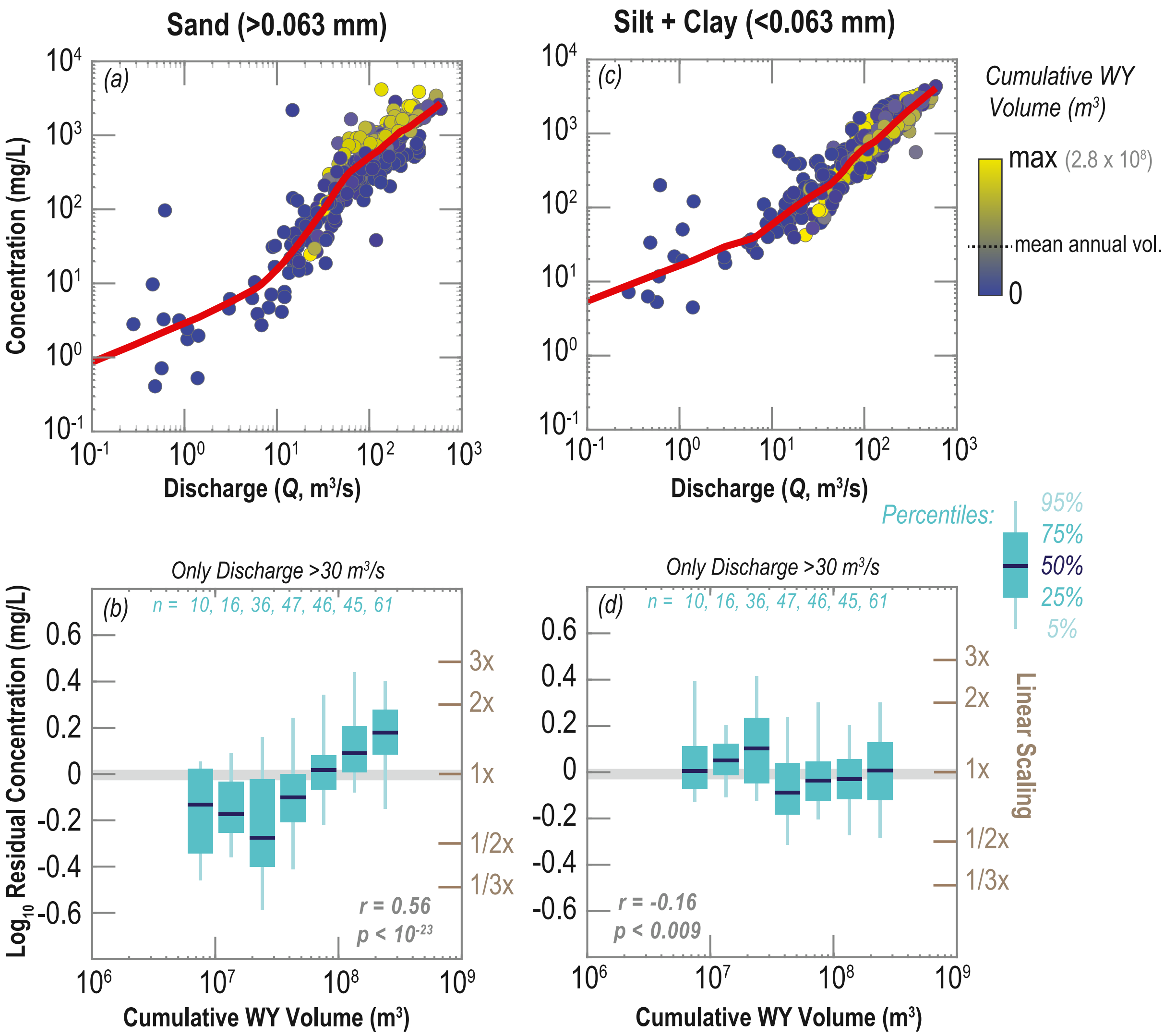

Figure 3. Relationships among instantaneous discharge, suspended-sediment concentration, and antecedent hydrologic conditions, represented by cumulative water year (WY) volume discharged at the time of sampling, for sand (a, b) and finer-grained sediment (silt and clay; c, d). Red lines in panels (a, c) show locally estimated scatterplot smoothing (LOESS) regression fit. Samples representing wetter antecedent conditions (yellow end of cumulative-volume color spectrum) are more likely to have greater sand concentrations (positive residuals, panel b) whereas finer sediment residuals are largely unchanged under wetter antecedent conditions (d). "Residuals" refers to difference between measured values and LOESS regression line fit for cumulative water year volume plotted against sand concentration.

consistent with efficient fluvial export of landslide material reported in other steep, mountainous terrain (Gayer et al., 2025). By the end of very wet seasons, the lower river receives sand not only from supply released during recent, late-season storms, but also from the earlier-season sources that continue shedding sediment. Interestingly, the intraseasonal sand-supply increase within wet years did not appear to persist from the end of one wet year to the next sampled flood 1–2 years later (Figure 4; Table S1 in Supporting Information S1), which could have resulted from vegetation restabilizing slopes, gradual export during low flows including as bedload transport not captured by our sampling (bedload may represent a significant, unmeasured fraction of total sediment flux from this watershed), or, less likely in this setting, failures having exhausted the mobile regolith supply on a localized scale. Detecting the increased sediment supply in the lowermost river's SSC record depends upon a watershed having sufficient connectivity to transmit that signal (Clark et al., 2024; Fryirs, 2017; Wohl et al., 2019), aided here by a lack of mainstem-river dams. Landslides are known to increase the coarse sediment supply to streams, with the downstream effects being a function of grain size and flow competence (Attal et al., 2015; Chen et al., 2018; Graf et al., 2024; Piantini et al., 2021; Roda-Boluda et al., 2018; Xie et al., 2024); this study newly demonstrates the increasing role of coarse hillslope sediment supply in the fluvial system over a winter season as

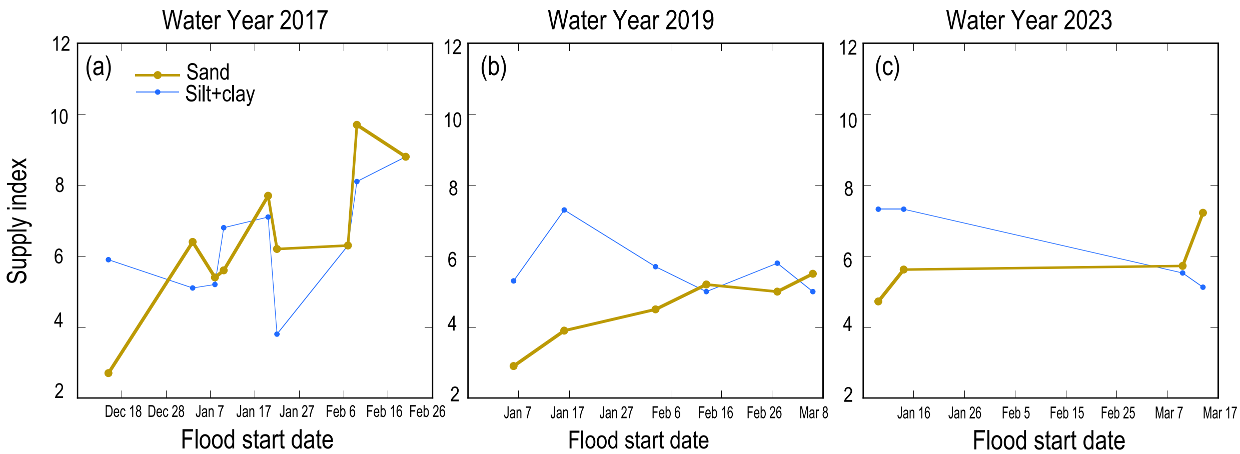

Figure 4. Supply indices calculated for sand and silt-plus-clay for individual floods (events near or above the 2-year peak-flow magnitude) based on discharge–SSC regression relationships for samples collected during each flood in panel (a) water year 2017, (b) water year 2019, and (c) water year 2023. Regressions were forced through the origin for each event, and the index value represents the slope of the resulting linear-regression line. Higher indices (steeper regression slopes) indicate higher sediment concentration for a given discharge, that is, greater sediment supply. Table S1 in Supporting Information S1 lists supply indices for all floods in the sampled record; Figure S3 in Supporting Information S1 shows example calculations for individual floods.

repeated storms progress to create an extreme wet year. Our data provide empirical support to model predictions of landslide-driven coarser fluvial sediment fluxes in warmer climate scenarios (Xie et al., 2024) and affirm the idea that sampling fluvial sediment at high temporal resolution during floods could be used to detect and perhaps estimate the magnitude of geo-climatic hazards where direct landslide monitoring is infeasible (Vergara et al., 2022).

The floods we documented were numerous, and though not extreme in size (largest events just over 10-year peaks; Figure 2), their cumulative effect in the nearshore zone approached that of a 100-year flood. A 100-year flood in January 1982 (~840 m^3/s peak, 40% above the largest flood in our sampled record) deposited ~300,000 m^3 of sediment that caused 4 m of vertical accretion in the San Lorenzo River delta and seaward progradation of several hundred meters, with the new deposits eroded by wave action and longshore transport

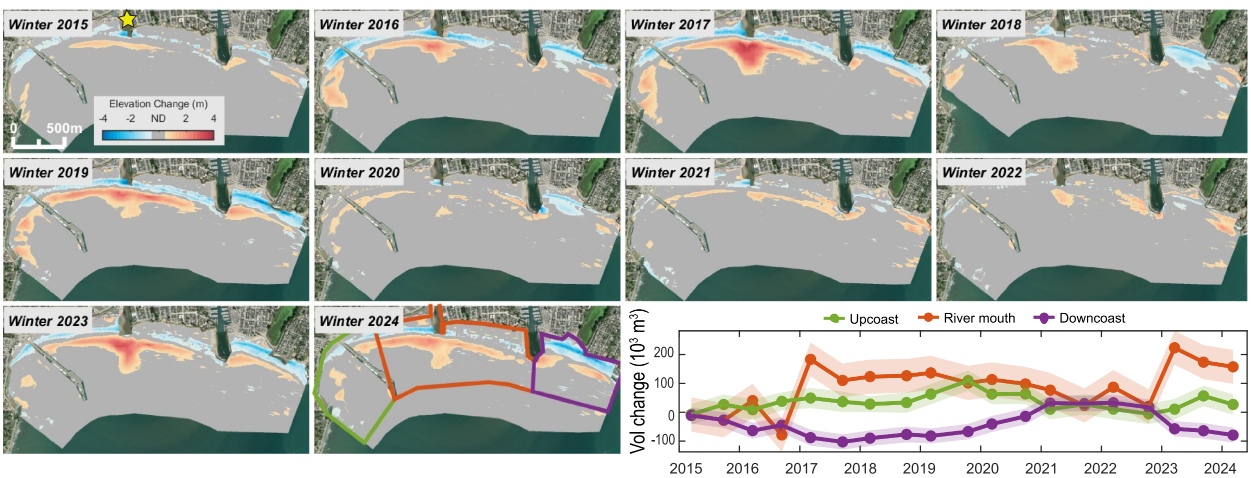

Figure 5. Maps showing elevation change surveyed in a 2.5-km^2 coastal area over 10 winter seasons, 2015 through 2024, and (at lower right) volume change calculated for biannual time intervals in three portions of the surveyed area (upcoast, river mouth, and downcoast regions depicted on the winter 2024 map panel; the longshore current direction is west-to-east). The San Lorenzo River mouth is at the top center of the mapped region (yellow star on 2015 panel). For each time step, the elevation and volume differences are calculated with respect to the topographic/bathymetric surfaces measured in fall 2014. New aggradation in extreme wet years (2017, 2023) contrasts with the lack of new deposition in extreme dry years (2015, 2020, and 2021). Accretion in the river-mouth delta was greatest in 2017 and 2023 (orange line on volume plot), whereas the downcoast survey region (in purple) received the most new sediment in 2020–2022, presumably from gradual longshore transport of sand from the river mouth. The upcoast region (green) does not receive substantial fluvial sediment supply as no other large watershed is present for tens of kilometers upcoast. Figure S4 in Supporting Information S1 shows cross-shore profiles.

over several years (Hicks & Inman, 1987). Thus, even without a singular catastrophic (50- or 100-year) flood, extreme wet years developing through repeated atmospheric-river storms bringing 2- to 10-year floods, as happened in three years of this study, still contribute significant quantities of sand from the perspective of littoral sediment supply and nearshore morphodynamic evolution.

The timescale of recovery after the extreme wet years in our sampling record appeared to be more rapid for fluvial sediment (1–2 years; Figure 4) than for the coastal system, where the 2017 accretion signal in the river-mouth delta gradually decayed over 4–5 years as sediment moved downdrift (eastward; Figure 5, Figure S4 in Supporting Information S1). Comparing our findings to those from other coastal California watersheds, longer recovery timescales were documented after extreme wet years in the Eel River, 350 km to the north, and the Santa Clara River, 400 km south. The Eel River's flood of record, a >200-year event in 1964, led to a proportionally greater increase in suspended-sand concentrations than silt-plus-clay (consistent with our findings), and the influence of that flood on the rating curve persisted for more than 20 years (Gray, 2018; Warrick et al., 2013). After the Santa Clara River's flood of record in 2005, delta progradation and downdrift beach widening persisted for more than 15 years and spanned several kilometers down-coast (Barnard & Warrick, 2010; Warrick et al., 2023). Our results are not directly comparable with the latter two events, though, because they involved relatively larger singular events and because, given their order-of-magnitude larger watersheds (9,540 and 4,220 km^2, respectively) and floodplains that store sediment, a longer-lasting, buffered sediment release would be expected (Stillwater Sciences, 2008; Warrick et al., 2023). Recovery times for fluvial sediment after storm-driven disturbance of smaller watersheds (order 10^2 km^2) in tropical and temperate latitudes seem to require around 1–6 years (this study; Abbott et al. (2018) in New Zealand; Gayer et al. (2025) on La Réunion Island; Grande et al. (2021) in Puerto Rico). Further investigations would be valuable for resolving disturbance-recovery times in watersheds of various sizes.

The substantial fluvial sand delivery during extreme wet years on the scale documented in this study provides new coastal sand resources, counteracting some of the anticipated beach loss on the U.S. west coast as sea level rises (e.g., Vitousek et al., 2017); our work highlights the challenge of applying models to predict future coastal change assuming static sediment supply. Flooding and landslides from repeated atmospheric-river storms are undeniably hazardous and costly, and large sediment pulses on developed coastlines require additional management (e.g., harbor dredging) and can negatively affect some coastal ecosystems. While acknowledging these challenges, it is notable that the sedimentary impacts of extreme wet years—the delivery of disproportionately coarser-grained, sand-dominated material in the later floods of a wet year, and multiyear coastal residence time of the new sediment—could have potential societal and economic benefits by reducing the need for beach nourishment (Griggs, 2024; Warrick et al., 2022) and increasing the coastal buffering capacity against wave erosion and landward beach retreat under sea-level rise.

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Data Availability Statement

All data discussed in this paper are publicly available. The fluvial suspended-sediment data record for the San Lorenzo River is available from East and Ritchie (2024). The coastal topographic and bathymetric survey data can be downloaded from Snyder et al. (2024). Discharge records from the San Lorenzo River at gaging station 11161000 can be accessed at https://waterdata.usgs.gov/monitoring-location/11161000 (U.S. Geological Survey, 2025). Additional information on bed sediment grain size in the San Lorenzo River immediately upstream from the sampling location in Santa Cruz, California, can be found in Dow (2024). Information on geochemical analyses (not discussed in this paper) from the San Lorenzo River water and sediment samples is available from Conaway et al. (2013) and Campbell et al. (2022). The base map shown in Figure 1a is a product of the USGS National Map made available by the USGS National Geospatial Program (https://www.usgs.gov/programs/national-geospatial-program/national-map).

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Erratum

The originally published version of this article inadvertently included the following in the Acknowledgments: "Open Access funding enabled and organized by Projekt DEAL." The error has been corrected, and this may be considered the authoritative version of record.