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Retention of alluvial sediment in the tidal delta of a river draining a small, mountainous coastal watershed

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ABSTRACT

Small mountainous coastal watersheds are thought to be responsible for transporting disproportionately large volumes of sediment to the global ocean. In comparison with low-relief passive margin rivers, their geologic setting is associated with high rates of sediment production, high peak flows due to uniformity in runoff lag-times, and limited floodplain development. However, mountainous watersheds are often associated with estuarine deltas, and because the stream gauges used to calculate water and sediment fluxes tend to be located above the head of tides, the relative magnitude of sediment discharged to the ocean vs. retained in deltas is uncertain. The aim of this study was to determine the estuarine trap efficiency for the Salinas River in central California (USA), a watershed known both for its extremely high rate of sediment production and its extensive lowland delta, thereby helping to resolve the role of estuarine deltas in ocean sediment discharge. Sediment retention rates were calculated for the Late Holocene, using soil maps to estimate the areal extent of the delta prior to land reclamation, and radionuclide, pollen, pollution, and flood chronologies in concert with sediment bulk density measurements to constrain deposition rates. Results suggest that less than 1% of the sediment delivered to the coastal zone by the river was retained in the estuarine delta. Deposition rates distant from distributary channels matched long-term rates of sea level rise, suggesting that the formation of accommodation space acted as a primary control on sediment accretion. However, along tidal-fluvial distributary channels, accretion rates were much greater, and discrete flood layers were present, suggesting that accretion along distributaries was driven by flood events. In addition, long-term variability in sediment accretion rates broadly matched other records of alluvial flooding in central and southern California, suggesting that high precipitation intervals leave an imprint – although subtle – in the sedimentary record of estuaries. By documenting high sediment discharge to the ocean (99% of fluvial load), this study highlights the importance of small mountainous watersheds in global oceanic sediment transport, and further emphasizes the joint roles of accommodation space formation and sediment supply in controlling rates of estuarine sediment accretion.

KEYWORDS

hydrology; watershed; sediment yield; Holocene; tectonic; sand

1. INTRODUCTION

Relative to their area, small ($\leq 10^4$ km^2) mountainous coastal watersheds are responsible for transporting a disproportionately large quantity of sediment to the ocean (Milliman and Syvitski, 1992). Steep slopes associated with active-margin plate tectonics are associated with greater rates of sediment production, erosion and stream power (Pazzaglia et al., 1998). In contrast with larger basins, smaller, steeper watersheds tend to have greater uniformity in river runoff time lags, flashy flow peaks (Meybeck et al., 2003), and less area in which to store sediment carried by high discharge events (Farnsworth and Milliman, 2003). Consequently, the U.S. Pacific coast, and California in particular, is responsible for transmitting large volumes of sediment to the coastal zone during episodic events (Inman and Jenkins, 1999). Of the largest daily sediment loads recorded for U.S. rivers, 22 of 25 are shared among three California coastal basins: the Eel, Salinas, and Santa Clara (Farnsworth and Milliman, 2003). Sharply rising and falling hydrographs follow rainfall events, as stormwater is rapidly routed through mountainous watersheds (Wheatcroft et al., 2010). In addition, coastal California also experiences other episodic events, such as wildfires, earthquakes, landslides, atmospheric rivers, and ENSO-driven weather, which may enhance sediment yields, or exacerbate peak flows (DWR, 2009; Finnegan and Balco, 2013). Given the episodic nature of large winter streamflow events and the high sediment yield of its steep coastal basins, hyperpycnal flows can develop in the coastal ocean at river mouths (Warrick et al., 2008). These hyperpycnal flows carry sediment away from littoral cells and into offshore basins (Warrick and Milliman, 2003).

This process of sediment export from California coastal watersheds, where extreme events result in direct sediment delivery to the continental shelf, slope, or submarine canyons, stands in strong contrast to coastal sediment transport in passive margin rivers, where floodplains, estuaries, deltas and coastal wetlands operate efficiently at almost completely capturing fluvial sediment (Marcus and Kearney, 1991; Meade, 1982; Noe and Hupp, 2009). In fact, in many Atlantic estuaries sediment transport is landward (Benninger and Wells, 1993; Donnague et al., 1989). However, impounding barrier beaches found on the Pacific coast of North America comprise a significant obstruction to seaward sediment transport, and studies have suggested that coastal estuaries in California may trap a significant portion of sediments eroded from their watersheds. At the Tijuana River Estuary, flood deposits as thick as 8-cm were found in coastal marsh 2 km north of the river channel in response to a ten-year flood event (Cahoon et al., 1996). Analysis of repeat bathymetric surveys, sediment composition, and soil erosion suggest that Tomales Bay traps 95% or more of fluvial sediment delivered from its drainage basin (Rooney and Smith, 1999). At Estero Punta Banda in northern Baja California, historic aerial photography coupled with bathymetric surveys and sediment load analysis suggest estuarine trapping efficiency of nearly 100% following a series of heavy rainfall years (Ortiz et al., 2003), with subsequent stabilization of sediment deposits by vegetation (Watson and Hinojosa Corona, 2017). At Morro Bay, analysis of repeat bathymetric surveys, sediment deposition, and flow events suggest that the Bay traps 100% of fluvial sediment (~10^5 t yr^{-1}) in addition to 10^5 t yr^{-1} of littoral sediment (Thompson et al., 2002). Overall, these studies suggest that in some Californian estuaries, trapping of fluvial sediment may be significant, reducing or completely eliminating oceanic discharge.

The goal of this study was to better understand the fate of sediment eroded from small, tectonically active watersheds by estimating the proportion of sediment retained by the historic tidal delta and floodplain for the Salinas River, on California's central coast, during the Late Holocene. This watershed comprises an ideal case study due to its lengthy monitoring record, which is necessary for estimating mean sediment fluxes from highly episodic watersheds (Farnsworth and Milliman, 2003; Inman and Jenkins, 1999), and its abundance of lowland wetlands which record fluvial discharge (Gray et al., 2018). A reconstruction of historic estuarine spatial extent was coupled with analysis of chronologically-constrained sediment deposits to estimate the mass of sediment deposited in the tidal delta of the Salinas River, relative to estimates of sediment discharge from rating-curve analysis. Textural gradients were used to infer sediment transport vectors, while elemental composition was used to compare sediment provenance across the delta. In addition, this study addresses societal concerns: sediment is both an aquatic ecosystem stressor and necessary for beach and coastal wetland sustainability for California's central coast. Better knowledge of sediment transport pathways contributes to the development of sustainable sediment management practices.

2. STUDY AREA

The Salinas basin is the largest of the Californian central coast watersheds, comprising 10^4 km^2 (Carter and Resh, 2005) (Fig. 1). Topography in the basin consists of steeply sloped uplands in the Santa Lucia and Gabilan ranges, with peaks reaching upwards of 1500 m, converging to a gently inclined fertile valley bordered by sloping terraces and alluvial fans. Flow on the Salinas measured just upstream of potential tidal influence ranges from 0 m^3 s^{-1} during the late summer dry season to 3000 m^3 s^{-1} during floods; the climate is dry summer subtropical with rainfall and runoff events concentrated in the November through March period. Transmission losses indicate substantial groundwater recharge through permeable Salinas River bed sediments (Planert and Williams, 1995).

Historically, the Salinas River shared a perennial common outlet to the ocean with a series of estuarine sloughs in central Monterey Bay, near the head of the Monterey Submarine Canyon (Hermann, 1879; Johnson and Rodgers, 1854) (Fig. 2). The Monterey Submarine Canyon is one the largest on the Pacific coastal of North America, extends to at least 90 km offshore and to a depth of over 3km (Smith et al., 2005). Sediment that accumulates near the canyon is actively discharged to the abyssal plain via turbidity flows, mass wasting, landslides, and a form of bed load transport termed sandwave migration (Xu et al., 2008). In addition to this dynamic but usually perennial oceanic outlet, outlets formed episodically at two known locations to the south, where low points in fronting sand dunes occur (Fig. 2). Today, the Salinas River is managed to discharge directly to the ocean during floods (employing manual breaches), rather than being allowed to flow northward through its former distributaries. While the tide range at the former inlet is thought to be somewhat larger than it was historically due to the dredging of a deepwater harbor (Van Dyke and Wasson 2005), water control structures restrict tidal exchange across much of the former lower Salinas delta. Flow is managed to prevent flooding of valuable agricultural land, and much of the former aquatic habitats have been reclaimed for agriculture or grazing.

3. MATERIALS AND METHODS

3.1 Core retrieval and processing

Sediment cores were collected from seven sites located throughout the historic Salinas River delta, and one core was collected from a former ox-bow of the Arroyo Seco River, the largest undammed tributary of the Salinas River, now uplifted and partially impounded by landslides (Fig. 1) (Table 1). Sediment cores were split length-wise, described, and profiled using non-destructive techniques, including x-radiography and magnetic susceptibility. Cores were stored prior to analysis at 4° C, and sub-sampled at one to five-cm intervals for elemental analysis, particle size distribution, bulk density, and organic content.

Sediment accretion rates were determined using pollen, pollution, flood-deposit and radio-isotope chronologies. Near-surface sediments were analyzed for ^{137}Cs activity using a Canberra GL2020RS low energy germanium planar gamma spectrometer; the deepest horizon with detectable radiocesium was assigned a date of 1954 and peak values a date of 1963 (Foster and Walling, 1994). Seeds and rhizomes of wetland plants were dated using AMS ^{14}C dating after pre-treatment using a standard acid-base-acid method. Radiocarbon ages were corrected for δ^{13}C content, and calibrated using CALIB (ver. 7.1; Reimer et al., 2013; Stuvier et al., 2018) (Table 2). For the Arroyo Seco core, two additional ^{14}C dates from previously dated cores at the site aided in chronology development (Hiner et al. 2016). There was no concern about old ^{14}C derived from marine upwelling being incorporated into macrophtye material, as the wetland macrophytes are only periodically flooded and draw carbon dioxide from the atmosphere, as reflected in their δ^{13}C values (Watson et al. 2004), which are significantly lower than those found in algae and seagrasses, which do assimilate DIC (Simenstad and Wissmar 1985). Historic peaks in sediment lead concentration were assigned a date of 1974, coincident with the beginning of the phase-out of leaded gasoline (Finney and Huh, 1989). Brasicaceae pollen and *Sporormiella* fungal spores were used as isochronological markers for Moro Cojo slough where transitions from natural lands to pasture and from sugar beets to Brussels sprouts and broccoli recorded in agricultural census reports were clearly reflected in the palynomorph spectra. Sediments were processed for pollen and spores using standard methods (Faegri and Iverson, 1975); identification was made on a Nikon Eclipse E200 microscope, at 400 times magnification with reference to published pollen atlases (Kapp et al., 2000; McAndrews et al., 1973; Moore et al., 1991). Flood deposits on the active Salinas River were assigned ages based on known events (Gray et al., 2018). Age models were constructed using the radiocarbon dates and other isochronological markers (Fig. 3; Table 2; Supplemental Material) implementing a Bayesian Markov chain Monte Carlo approach using the R package BACON (Blaauw and Christen, 2011).

To measure particle size distribution, sediments were treated over several hours with multiple aliquots of heated hydrogen peroxide to remove fine and coarse organic particles, dispersed with a 5% solution of sodium hexametaphosphate (Gray et al., 2010), and introduced into a Beckman Coulter LS-230 laser diffraction granulometer with polarization differential intensity of scattered light (PIDS) for resolution to 0.045 µm. Sediments were analyzed for bulk density by drying a known volume of sediment to constant weight at 105°C, and for organic content by ashing for four hours at 550°C using loss on ignition (LOI), in both cases with the final cooling ramp conducted in a vacuum desiccator (Heiri et al., 2002).

Elemental concentrations were measured using inductively coupled plasma atomic emission spectroscopy (ICP-AES). Sediments were air-dried, ground to a fine powder, and pre-treated by four acid (hydrochloric, nitric, perchloric, and hydrofluoric) near-total digestion. After leaching, sample solutions were analyzed to obtain the concentrations of 33 elements; nine elements were routinely below detection limits and not used in data analysis. Elemental data were normalized to 100% on a LOI-free basis. A standard reference material was used to determine dissolution efficiency and accuracy of bulk elemental measurements (Supplemental Material). Potential diagenic remobilization was assessed using downcore trends for iron and manganese, which are soluble under reducing conditions but re-precipitate under oxic-suboxic conditions (Singh and Nakak, 2009).

3.2 Data analysis

Because the Salinas delta integrated sediment sources from several sub-watersheds, elemental compositions were used to estimate the proportional contribution of Salinas sediment. Prior to analysis, values were adjusted for the influence of grain size and organic content by regressing the inclusive graphic mean (Folk, 1974) (or LOI) against elemental concentrations; where relationships were significant and a minimum threshold of variance explanation was exceeded (r^2>~0.10), predicted concentrations modeled by the regression equation were subtracted from LOI-free elemental concentrations. To assess separation between sites, geochemical data was collapsed to five significant principal components. An index (Renkonen, 1938) previously applied to assess geochemical similarity (Battin et al., 2004) was calculated to describe spatial and temporal geochemical similarity between sub-estuaries and the Salinas lagoon. The Renkonen index was calculated as:

$$PS = \sum_{l}^{i} \min(p_{1,i}, p_{r,i})$$

where PS was percentage similarity, $p_{1,i}$ was the sample concentration for element i, and $p_{r,i}$ the reference concentration for element i. Percentage similarity ranged from 0 to 1, where 0 indicated no similarity, and unity indicates identical concentrations. Here, we calculated p_r from contemporary Salinas Lagoon sediments to compare sediment geochemistry from sub-estuaries, where sediment is derived from mixed sources. Two separate analyses were completed: one where elemental composition varied with abundance, and a second conducted on z-scores to downplay the contribution of more common elements.

Direction of sediment transport through the historic Salinas delta was investigated by implementing a simple (i.e., non-gridded) sediment trend analysis. Sediment particle size distribution data was used to map mean sediment size, and skew (Folk, 1974). Sediment particle size distributions were used to infer sediment transfer functions and transport direction, as transport and modeling studies describe sediments transported downstream as finer and more negatively skewed than source material and lag deposits (MacLaren, 1981; MacLaren and Bowles, 1985).

3.3 Geospatial Analysis

To calculate the mid-nineteenth century extent of the tidal delta of Salinas River, U.S. Coastal Survey charts (Johnson and Rodgers, 1854), Geological Survey (USGS 1912; 1913; 1914; 1917), and water resource maps (Cox, 1877; Hare 1898; Hare, 1916; Lapham and Heileman, 1901) were overlaid with contemporary data layers including elevation, National Wetlands Inventory, and the USDA National Resources Conservation Service Soil Survey Geographic Database (SSURGO) in ArcGIS version 10 (ESRI, Redlands, CA, USA). Newspaper accounts, shipping records, and survey notes were used to reconstruct the extent of tidal exchange (e.g. Castroville Argus, 1870; Crespi, 1769 in Brown, 2002; Daily Alta California, 1861; Davidson, 1889;

Foreman, 1867; Hermann, 1879). Historic sediment deposition in the Salinas River estuarine delta (in metric t yr^{-1}) was calculated as the product of the historic tidal delta extent, spatially averaged deposition rates and sediment bulk density values. To estimate sediment mass accumulation rates for sediments originating from the Salinas basin, spatially averaged similarity indices were multiplied by deposition weights. These values were then compared to published load values for the Salinas basin, adjusted for dam-trapped sediment.

4. RESULTS

4.1 Sediment Deposition Rates and Patterns

Chronologic control provided by ^{14}C and ^{137}Cs dates interpreted in concert with sediment lead concentrations, pollen analysis, and sediment density data were used to infer mean accretion rates that decreased down the watershed (Fig. 4; 5). Accretion values decreased from 0.30 cm yr^{-1} at Arroyo Seco, to 0.29 cm yr^{-1} at the Salinas Lagoon, 0.12 cm yr^{-1} at Tembladero Slough, and 0.16 cm yr^{-1} at the Harbor. This is equivalent to 3.2 kg m^{-2} yr^{-1} of mineral (non-organic) sediment deposition at Arroyo Seco, 3.3 kg m^{-2} yr^{-1} at the Salinas Lagoon, 1.4 kg m-^{2} yr^{-1} at Tembladero Slough, and 2.0 kg m^{-2} yr^{-1} at the Harbor. Sediment accretion rates were similar and much lower along the estuarine sloughs: 0.083 cm yr^{-1} at Lower Moro Cojo Slough, 0.084 cm yr^{-1} at Upper Moro Cojo Slough, 0.093 cm yr^{-1} at Yampah, and 0.083 cm yr^{-1} at Azevedo. These vertical accretion rates were equivalent to 0.78 kg m^{-2} yr^{-1} at Lower Moro Cojo Slough, 0.68 kg m^{-2} yr^{-1} at Upper Moro Cojo Slough, 0.54 kg m^{-2} yr^{-1} at Yampah, and 0.36 kg m^{-2} yr^{-1} at Azevedo. Higher accumulation rates were found for younger records, for higher energy environments, and declined through the delta with distance from the Salinas River distributaries.

For records that possessed well-defined, pre-historic and recent intervals (Tembladero, Moro Cojo, and Elkhorn Slough), some post-settlement rates of sediment accumulation (in cm yr^{-1}) were found to be higher than pre-settlement (Yampah and Tembladero Sloughs), while some were not (Moro Cojo Slough and Azevedo). Autocompaction was not a factor, as surface deposits were not less dense nor more porous than deeper sediment deposits.

With respect to the longer-term history of sediment deposition, some degree of concordance was found between sub-estuaries: deposition rates were found to be somewhat higher than average during the early part of the record (apart from an interval from 5000 to 4500 cal. yr. B.P.), declining to lower values centered on or around the interval 2500 to 1500 cal. yr. B.P., and increasing during the Little Ice Age (LIA) and through European-American settlement (Figs. 4-6). A longer-term history of sediment deposition was produced for the broader Salinas River Estuary from cores that record Late- Holocene deposition rates by binning each 500 yr increment, and standardizing by subtracting core-specific mean values, dividing by core-specific standard deviation values, and summing residuals (Fig. 6a). This record of sediment deposition reflects other paleoprecipitation indicators, including those reconstructed from interpretation of sediments from central California, including south San Francisco Bay (Watson and Byrne 2013), at Abbott Lake, which we also cored as part of this study (Hiner et al. 2016), and nearby Zaca Lake (Kirby et al., 2014), as well as records from southern California, including the Mojave playas (Miller et al., 2010), San Joaquin Marsh (Davis 2002), Lake Elsinore; Kirby et al. 2010, Lower Bear Lake; Kirby et al. 2012) (Fig. 6b). We found higher rates of estuarine sediment deposition during intervals reconstructed as wetter through other proxies, from the 5-3,000 cal. yr. B.P. and during the LIA, and lower rates of sediment mass accumulation during periods reconstructed as drier, such as the Medieval Climate Anomaly, and the Late Holocene dry period (2,700-2,000 cal. yr. B.P; Dingemans et al. 2014).

4.2 Sediment composition

Analysis of sediment texture showed that sediment grain size decreased downstream from the Salinas Lagoon and through its sub-estuaries, from a composition of about half sand and half fines in the Lagoon proper, to about 25% sand and 75% silt and clay at the junction with Tembladero Slough and in the Harbor, and 99-100% fines at Moro Cojo and Elkhorn Slough (Fig. 7). There was more variability between samples for the Salinas Lagoon, Tembladero Slough, and Harbor, suggesting event-based deposition for these locations (Gray et al., 2018) (Supplemental Material). Between-sample variability was low for the estuarine wetlands that were more distant from the Salinas mainstem. Plots of average sediment grain size distribution from lagoon and sub-estuary cores strongly suggest a common source of sediment, with locations downstream of the Salinas River proper receiving finer, better sorted, and more negatively skewed sediment populations (Fig. 7). Because transport and modeling studies describe sediments in transit as finer and more negatively (fine) skewed than source material and lag deposits (MacLaren, 1981; MacLaren and Bowles, 1985), these observations suggest that sediment transport direction is from the Salinas Lagoon to Tembladero Slough to the Harbor, and from there jointly to the upper estuaries. (Fig. 7).

The elements sodium and lead were removed from the PCA due to low individual Kaiser-Meyer-Olkin (KMO) scores (<0.45); Bartlett's test of sphericity was statistically significant ($p<0.0001$) indicating that the data was factorizable. PCA revealed five components that had eigenvalues greater than one and which explained 29.6%, 17.7%, 12.1%, 9.7%, and 7.0% of the variance respectively. Scatterplots of PCA scores did not reveal significant separation in sediment composition between coring sites (Supplemental Material). Most elements had significant relationship with more than one axis (Supplemental Material). After adjusting for the effects of grain size, and sediment organic content, we found that average geochemical similarity to the Salinas River Lagoon sediments was 90±6.6% (mean ± standard deviation) for Tembladero Slough, 96±2.2% for Lower Moro Cojo Slough, 95±5.5% for Upper Moro Cojo Slough, 83±8.0% for Lower Elkhorn Slough, 87±5.8% for Upper Elkhorn Slough. Geochemical similarity between the Arroyo Seco sediments and Salinas Lagoon sediments was 90±5.4%. Patterns of geochemical similarity were comparable for raw and standardized values (r^2=0.83). These results suggest that the lithogenic sediments deposited in the northerly estuaries were derived primarily from the Salinas River watershed. Rates of elemental recovery were excellent and down-core trends in redox sensitive metals suggest elemental mobility only for the Arroyo Seco core (Supplemental Material).

4.3 Geospatial analysis

Potential estuarine extent was mapped from historic data sources and compared with contemporary geospatial data. Good correspondence was found between estuarine extent from historic maps and an elevation contour of <3 m NAVD88 (80% of the areas coincide) apart from present-day agricultural areas that have been graded (3% of the areas). Better correspondence (95%) was found between historic estuarine extent and the Monterey County Soil Survey soil types Alviso silty clay loam, rindge muck, water, and marine-water. Alviso soils are mineral soils formed by alluvium from primarily sedimentary rock, found in level basins and tidal flats flushed by sea water and varying remains and alluvium in low-slope geographic settings such marshes, sloughs, river channels, and deltas (Soil Service Staff 2015). Jointly, these soil types are suggestive of estuarine conditions. Calculating estuarine areal extent based on soil types listed above produced an estimate of 2,190 hectares (21,900,000 m^2).

We estimated a mean annual mass accumulation rate as the product of spatially averaged local deposition rates and lithogenic sediment density derived from mean core data to produce a yearly average deposition flux of 10^3 - 10^4 tons of non-organic sediment deposition per year (4,500 t a^{-1} for the Elkhorn Slough, 3,300 t a^{-1} for the Moro Cojo Slough, and 8,800 t a^{-1} for Tembladero Slough and the lower Salinas River). In comparison, published estimates for average suspended Salinas River loads sum to 10^6 tons yr^{-1} (Farnsworth and Milliman 2003; Gray et al., 2015; Inman and Jenkins 1999) or as much as 10^7 tons yr^{-1} when adjusted for reservoir trapping (Willis and Griggs, 2003) and the potential impact of infrequent seismic events. This analysis suggests that a maximum of 1%, or less, of the river load was ultimately deposited in the tidal delta.

5. DISCUSSION

Over the last 5,000 years, a minor percentage of Salinas basin sediment was retained by the historic delta and estuary. On average, this mass summed to less than 10^4 tons yr^{-1}, and was very likely delivered in an intermittent fashion, resulting from the highly episodic event-based nature of fluvial discharge along the Californian central coast (Inman and Jenkins, 1999). Based on suspended sediment flux rates established from contemporary event monitoring, this suggests that for the Late Holocene, the estimated trap efficiency of the historic estuary and delta was on the order of 1%, or less. While we were unable to completely constrain uncertainty in the contribution of Salinas River sediment vs. local sediment sources in estuarine accumulation, differences in proportions of sediment would not change the conclusions of the study (high bypass rates), and grain size profiles suggest northerly transport of sediment (Fig. 7). Sediment trapping efficiency was probably much greater during the early Holocene. Studies of that period suggest rapid sea level rise flooded the Pajaro and Salinas River valleys, which were deeply entrenched into their alluvial plains during the Pleistocene sea level low stand (Chin et al., 1988), creating extensive estuaries (Dupré, 1975; Masters and Aiello, 2007). We interpret the trap efficiency of the Salinas delta as similar to that described for other incised-valley fill systems. High rates of estuarine sediment trapping likely occurred during sea level transgression, followed by high rates of by-pass for the Late Holocene, as in-filled basins have converted to floodplains, and channels have shoaled (Roy, 1994).

Although the amount of sediment trapped by the estuary was found to be low relative to the overall load, there were some spatial and temporal variations in sediment accumulation rates. While rates of sediment accretion, especially longer-term records, largely matched that of sea level rise (Fig. 7), variability in sediment accumulation rates appeared in phase with pluvial episodes reconstructed using lake level and run-off proxies across central and southern California (Fig. 6). While it is not clear that flood-derived sedimentation increased the overall trapping efficiency of the system to a measurable degree, by considering all of the sedimentation records jointly, we did found subtle evidence that climate variability left an imprint on the sedimentation record. And in addition to temporal variation, there were also spatial variations in aggradation. Accumulation rates adjacent to tidal-fluvial channels were up to an order of magnitude greater than they were more distant from tidal-fluvial channels. However, these high aggradation rates adjacent to distributary channels likely also contribute to the regular avulsion of these tidal-fluvial channels between active and abandoned (or semi-abandoned) distributaries, which has been observed during historic times for both the Salinas and other estuarine deltas in California (Watson et al., 2011; Gray et al., 2016b; Gray et al., 2018). Overall, our analysis of sediment accumulation rates argues that while the formation of accommodation space resulting from sea level rise acts as a primary control on estuarine deposition, climate variability, and channel avulsion also play roles in sediment accumulation in deltaic estuaries that drain steep mountainous watersheds on active margins.

This study somewhat contradicts contemporary research that documents high sediment trapping rates for California estuaries (Cahoon et al., 1996; Ortiz et al., 2003; Rooney and Smith, 1999). Because these past studies have focused on deposition at the scale of individual events to decades, they may be subject to bias associated with the observed inverse relationship between accumulation rates and measurement interval (Sadler, 1991), where short term rates reflect gross rather than net deposition (e.g. Van Maldegem et al., 1993). Alternatively, anthropogenic modifications to either watershed landuse or estuarine circulation (e.g., inlet stabilization, dredging) may overprint natural controls on sediment transport pathways and processes, and interactions with base level changes associated with glacial-interglacial cycles.

Our study found that over millennia (the Late Holocene), the Salinas River estuarine delta has retained only a small fraction of sediment eroded from its watershed. Where then does Salinas basin sediments go? Studies of seismic profiles and surface sediment texture along the Monterey shelf in the vicinity of the Salinas River, and onshore geologic studies have resulted in two separate schools of thought regarding shelf deposition: (1) that the Salinas River has discharged sediment to the Monterey Shelf south of the Monterey Canyon during the Holocene, and (2) that much of the Salinas River sediment is discharged to the Monterey Canyon system or transported off-shelf. Dupré proposed that the Monterey shelf has received little Holocene sediment, based on the large volume of valley fills for the Pajaro River, Elkhorn Slough, and Salinas Rivers (Dupré, 1975; 1984). And while oceanographic studies have found veneers of surface sediment on the Monterey shelf, and surface grain size profiles indicative of a Salinas River source for this sediment (Chin et al., 1988), because these sediments overlay an unconformity, which appears to be a Sangamon wave-cut platform, most have concluded that these sediments may date to the previous interglacial (126-110k yrs. B.P.; Shackleton et al., 2003) . More recent studies also report that during large events, half of the suspended load is ultimately deposited in the Monterey Canyon system (Johnson et al., 2001). Thus, most studies thus suggest that the majority of the sediment currently eroded from the Salinas watershed is ultimately routed into the submarine canyon system and/or dispersed off-shelf, and thus deposited below sea level low stands.

Global sediment flux surveys suggest that small mountainous watersheds in tectonically active regions account for a disproportionate share of sediment to the global ocean, in contrast with passive margins, where 95% of sediment is retained on alluvial planes, in wetlands and in estuaries (Meade, 1982). The example presented here provides strong evidence for high rates of oceanic discharge, at least during the slow rate of sea level rise found during the late Holocene. We have constrained that a relatively small portion of overall sediment flux was deposited within the historic estuary, with presumably large fluxes lost to the Monterey Canyon (Johnson et al., 2001; Smith et al., 2007). This hypothesis could be further tested by quantifying sediment fluxes from the Salinas River from the Monterey submarine channel system or overflow levees.

However, with respect to the ecologically valuable estuarine intertidal habitats supported by the historic Salinas River delta, a sediment accretion rate of up to 10^4 tons yr^{-1} was able to fill the accommodation space formed by Late Holocene rates of sea level rise (1.3 ± 0.19 mm a^{-1}; during the Late Holocene and 1.49 ± 0.95 mm a^{-1} over the last four decades; Reynolds and Simms, 2015). The disruption of natural sediment transport patterns, caused by disconnecting the Salinas River with its northerly distributary in the early 1900s, has coincided with an era of coastal wetland erosion and drowning (Van Dyke and Wasson, 2005), and thus probably contributed to negative ecological impacts at its estuarine sloughs. Although agricultural intensification has enhanced sediment delivery to the estuary (Byrd et al., 2004), the material eroded (sandy loams) lacks the cohesion of mud, and appears to not be playing a large role in wetland sediment accretion (Watson et al., 2011) and may be a decreasing sediment source with changing agricultural operations (Gray et al., 2016a). As reconnecting the Salinas River with its historic delta may not be practical due economic issues with flooding valuable agricultural lands, it may thus be necessary to envision other ways of meeting the sediment demand required for coastal wetland accretion during an era of enhanced sea level rise.

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CONTRIBUTORS

E.W., A.G., A.W., and G.P. collected the sediment cores, E.W. and A.G. analyzed the sediment cores, A.W. compiled and analyzed the historic maps and newspaper accounts, and georeferenced historic maps. E.W. took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript. G.P. supervised the project. All authors have approved the final article. The sponsors [NOAA, NSF, USDA] did not have any role in the study design, data collection, analysis or interpretation of the data, or the decision to submit the article for publication.

FIGURE CAPTIONS

Figure 1. The Salinas Basin, showing Arroyo Seco and tidal delta coring sites. The displayed hydrography was reconstructed from 19th century historic maps. Alisal Creek is a distributary of the Salinas River. On the eastern side of the lower valley, natural dams created by floodplain deposits created a series of lakes. Localities mentioned in the manuscript are depicted as (1) south San Francisco Bay; (2) Abbot Lake; (3) Mojave playa lakes; (4) Zaca Lake; (5) lower Bear Lake; (6) Lake Elsinore; (7) San Joaquin Marsh, Newport Bay.

Figure 2. Reclamation and tide gates have altered the hydrography of the Salinas River delta. During the 19th century, the Salinas River shared on oceanic outlet with a series of estuarine sloughs, including McClusky Slough, Elkhorn Slough, Moro Cojo Slough, and Tembladero Slough. Since the early 1900s a tide gate installed to prevent flooding of agricultural lands has limited discharge from the Salinas River lagoon through its northerly outlet. The lagoon is often closed off from the ocean, but during storms, an outlet to the ocean is breached manually. The tidal restrictions and wetlands shown as tidally restricted include some areas where the tidal restriction has since been removed.

Figure 3. Age-depth relationship for collected cores showing the 2-σ probability distribution for each radiocarbon date, and maximum and minimum accretion rates between each depth interval.

Figure 4. Cumulative sediment deposition as a function of time for eight Salinas basin and estuary sediment profiles. Sites with steeper slopes saw greater rates of sediment deposition.

Figure 5. Mean accumulation and sediment deposition rates across the depositional environments of the Salinas River. Grey band denotes the range of reconstructed late Holocene sea level rise rates in Monterey Bay and southern California (Reynolds and Simms 2015).

Figure 6. (A) Inorganic sediment accumulation rates, binned into five hundred year increments, and standardized by site; (B) mean composite rate of sediment accretion for the Salinas delta for all six cores expressed as normalized deviations from mean, compared with composite records of pluvial episodes, high run-off, or playa deposits recorded by sediment deposits from South San Francisco Bay (Watson and Byrne, 2013); Abbott Lake (Hiner et al., 2016); Zaca Lake (Kirby et al., 2014), and southern California lakes (Mojave Playas; Miller et al. 2010, Lake Elsinore; Kirby et al. 2010, Lower Bear Lake; Kirby et al. 2012). We also show the climatological relevant Late Holocene dry period (LHDP; 2700-2000 cal yr B.P.; Dingemans et al. 2014), the Medieval Climate Anomaly (1050–650 cal yr B.P.), and LIA (500-100 cal yr B.P.) (Masson-Delmotte et al. 2013). The zigzag symbol denotes the record length for Abbot and Zaca Lake.

Figure 7. (A) Mean particle size distribution for all cores and (B) gradients in mean sediment texture, (C) skewness, and (D) inferred transport vectors for the Salinas River delta. White represents upland, and medium gray the Pacific Ocean, with the fluvial-tidal portion of the estuary depicted in gradients for textural distributions and light gray for the transport vector map. Black circles denote coring locations.

TABLES

Table 1. Collected sediment cores

Site Name	Retrieval	Location	Length
Yampah	peat borer	36.8109°, -121.7485°	5.5 m
Azevedo	peat borer	36.8498°, -121.7581°	4.4 m
Lower Moro Cojo	vibracore	36.7988°, -121.7716°	4.2 m
Upper Moro Cojo	vibracore	36.7780°, -121.7378°	2.5 m
Tembladero	vibracore	36.7722°, -121.7885°	2.3 m
Harbor	vibracore	36.7959°, -121.7880°	2.7 m
Salinas Lagoon	vibracore	36.7376°, -121.7984°	0.5 m
Arroyo Seco	vibracore	36.2306°, -121.4804°	0.8 m

Table 2. AMS radiocarbon ages obtained from collected sediment cores. All radiocarbon ages were calibrated using Calib 7.1 (Stuiver et al. 2018). Calibrated ages include two standard deviations. *δ^{13}C=-25 assumed. *Scirpus* seeds could include seeds of the genera *Scirpus, Schoenoplectus* or *Bolboschoenus*

Core	**Depth (cm)**	**Laboratory Sample #**	**^{14}C Age ± σ**	**Cal yrs B.P. min**	**Cal yrs B.P. median**	**Cal yrs B.P. max**	**Material dated**	**δ^{13}C**
Tembladero	112	OS-70232	215 ± 35	0	184	311	*Ruppia* seeds	-16.8‰
Tembladero	151	OS-70233	400 ± 35	319	467	515	*Carex* seeds	-25*
Tembladero	237	OS-70253	1800 ± 40	1612	1731	1856	*Scirpus* seeds	-22.0‰
Lower Moro Cojo	175	OS-70241	2510 ± 55	2381	2538	2748	*Scirpus* seeds	-23.1‰
Lower Moro Cojo	375	OS-70239	3720 ± 55	3910	4067	4236	*Salicornia* roots	-26.7‰
Lower Moro Cojo	402	Beta-243584	4270 ± 40	4655	4846	4961	*Ruppia* seeds	-13.6‰
Upper Moro Cojo	244	OS-71117	2090 ± 25	1995	2062	2129	*Scirpus* seeds	-25*
Upper Moro Cojo	309	OS-71118	3500 ± 35	3650	3773	3868	*Scirpus* seeds	-26.3‰
Upper Moro Cojo	414	OS-71142	4140 ± 20	4576	4685	4821	*Ruppia* seeds,	-16.2‰
Harbor	95	UGAMS-11115	690 ± 25	565	661	681	*Salicornia* roots	-26.7‰
Harbor	195	UGAMS-11116	800 ± 25	677	712	758	*Salicornia* roots	-24.8‰
Harbor	230	UGAMS-11117	1420 ± 25	1291	1321	1356	*Salicornia* roots	-26.5‰
Yampah	75	CAMS-132991	170 ± 35	0	177	294	*Salicornia* fragments	-25*
Yampah	180	CAMS-132992	615 ± 50	539	602	665	*Salicornia* fragments	-25*
Yampah	275	CAMS-125886	3090 ± 45	3178	3296	3391	charcoal	-25*
Yampah	370	CAMS-125885	3050 ± 40	3158	3261	3367	*Salicornia* rhizomes	-25*
Yampah	425	CAMS-132990	3650 ± 40	3867	3972	4089	*Ruppia* seeds, *Salicornia* rhizomes	-25*
Yampah	510	CAMS-125884	4055 ± 40	4424	4539	4801	*Salicornia* rhizomes	-25*
Azevedo	70	CAMS-132995	455 ± 50	323	505	621	*Salicornia* seeds	-25*
Azevedo	135	CAMS-132994	1390 ± 40	1263	1307	1375	*Salicornia* seeds	-25*
Azevedo	192	CAMS-125887	2315 ± 40	2161	2337	2456	*Salicornia* seeds	-25*

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HIGHLIGHTS

- <1% of Salinas River sediments were trapped by its delta over the Late Holocene
- Away from distributary channels, sediment accumulation rates matched sea level rise
- Along tidal-fluvial distributaries, sediment deposition was driven by floods
- This high-relief coastal watershed delivers a large volume of sediment to the ocean