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Estuarine abandoned channel sedimentation rates record peak fluvial discharge magnitudes

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ABSTRACT

Fluvial sediment deposits can provide useful records of integrated watershed expressions including flood event magnitudes. However, floodplain and estuarine sediment deposits evolve through the interaction of watershed/marine sediment supply and transport characteristics with the local depositional environment. Thus extraction of watershed scale signals depends upon accounting for local scale effects on sediment deposition rates and character. This study presents an examination of the balance of fluvial sediment dynamics and local scale hydro-geomorphic controls on alluviation of an abandoned channel in the Salinas River Lagoon, CA. A set of three sediment cores contained discrete flood deposits that corresponded to the largest flood events over the period of accretion from 1969 to 2007. Sedimentation rates scaled with peak flood discharge and event scale sediment flux, but were not influenced by longer scale hydro-meteorological activities such as annual precipitation and water yield. Furthermore, the particle size distributions of flood deposits showed no relationship to event magnitudes. Both the responsiveness of sedimentation and unresponsiveness of particle size distributions to hydro-sedimentological event magnitudes appear to be controlled by aspects of local geomorphology that influence the connectivity of the abandoned channel to the Salinas River mainstem. Well-developed upstream plug bar formation precluded the entrainment of coarser bedload into the abandoned channel, while Salinas River mouth conditions (open/closed) in conjunction with tidal and storm surge conditions may play a role in influencing the delivery of coarser suspended load fractions. Channel adjacent sediment deposition can be valuable records of hydro-meteorological and sedimentological regimes, but local depositional settings may dominate the character of short term (interdecadal) signatures.

Keywords: paleohydrology; sedimentation rates; floodplains; estuaries; flood deposits;
Mediterranean climate; USA, California, Monterey Bay, Salinas River Lagoon

INTRODUCTION

Fluvial sediment deposits are the product of interactions between external processes that govern sediment delivery, and internal processes that affect sediment transport, deposition and preservation. At the largest regional to continental scales, and over thousands to millions of years, sediment delivery hinges on the balance of tectonics and climate, as illustrated by landscape evolution models (Howard et al., 1994; Lane et al., 1997; Tucker and Slingerland, 1997; Armitage et al., 2011). However, at watershed to regional scales, and over decades to centuries, sediment delivery is more directly explained by annual precipitation characteristics, seasonal precipitation variability, and landscape characteristics (e.g. relief, maximum elevation, area, land cover, and land use) (Dendy and Bolton, 1976; Milliman and Syvitski, 1992; Ludwig and Probst, 1998; Pasternack et al., 2001, de Vente et al., 2007). At subbasin to watershed scales, and over days to years, sediment delivery is again conditioned by factors operating over larger spatio-temporal scales, such as interdecadal scale anthropogenic impacts (Gilbert, 1917; Gottschalk, 1945; Trimble, 1997; Constantine et al., 2005; Warrick and Rubin, 2007). However, short term sediment delivery is most directly explained by weather-driven transient events (Park, 1992; Warrick and Farnsworth, 2009; Mayor et al., 2011) and transient disturbances such as wildfire (Warrick and Rubin, 2007; Warrick et al., 2012). The overall goal of this study was to investigate episodic sediment delivery to an estuarine lagoon over several decades in a dry-summer subtropical climate (i.e., Mediterranean) in order to determine the major factors controlling sedimentation.

Watersheds experiencing a Mediterranean climate exist at a metastable tipping point in terms of the genetic factors controlling water and sediment generation and export. Langbein and Schumm (1958) suggested that the semi-arid zone is a potent source of sediment flux, because rainfall is sufficient for effective erosion, but insufficient for the support of dense vegetation or

well-developed soils, both of which tend to reduce runoff, resist erosion, and decrease drainage density (Thornes, 1994; Osterkamp and Friedman, 2000). This mechanism is further enhanced for the dry-summer subtropical zone by the concentration of runoff and erosion during a short period of the year and high interannual variability in total flow and flood peaks (Baker, 1977; McMahon et al., 2007).

Further precarious dynamism stems from an array of climate-related disturbance types that render semi-arid watersheds particularly vulnerable to erosion, and those in the dry-summer subtropical zone even more so. The largest, rarest floods under these climatic regimes are more extreme than for many other climates (Baker, 1977; Costa, 1987) and they account for a disproportionate amount of sediment yield (Warrick and Farnsworth, 2009; Gonzalez-Hidalgo et al., 2010, Warrick et al., 2013). For example, greater than 90% of sediment exported from many coastal central and southern California watersheds is produced during events that represent less than 1% of the hydrologic records (Farnsworth and Warrick, 2007). Wildfire recurrence interval is the shortest in these regions (Malamud et al., 2005) and recovery from fire is slow (Mayor et al., 2007), with low resilience after human-influenced vegetative conversion from shrubland to grassland (Gabet and Dunne, 2002).

Despite a global tendency for stratigraphic preservation of delivered sediment to decrease with increasing timescale of investigation (Sadler, 1981) due to the distribution of erosional/non-deposition hiatuses (Sadler, 1999), millennial scale paleo-environmental studies in dry-summer subtropical watersheds of California have reported an opposite effect in which apparent deposition rates increase with record length (Kirchner et al, 2001; Constantine et al., 2003). This is partly explained by climatic change causing an inter-millennial decrease in event frequency and intensity relative to stormy conditions during the Pleistocene/Holocene transition (Johnson, 1977; Adam

and West, 1983; Rypins et al., 1989; Grigg and Whitlock, 1998; Beaty and Taylor, 2009). An additional factor is the dominant role that rare, high-intensity floods play in the interdecadal to millennial scale flux of sediment from dry summer subtropical basins. In these systems longer time periods of observation (or sedimentation) result in greater chances for an extreme event to occur in that domain, which can dramatically increase average sedimentation rates (Schumer and Jerolmack, 2009).

Sedimentary records under event-dominated hydro-sedimentological regimes may or may not bear decipherable event scale signatures depending on the character and magnitude of local factors affecting sediment deposition and preservation. Transport, deposition and resuspension of sediments delivered to coastal marine settings are influenced by fluvial plume characteristics, delta/estuarine dynamics, coastal currents, tidal and wind-driven wave regimes (van Rijn, 1993). The resultant accreted sediments are often prone to bioturbation, which can impose event magnitude thresholds on preservation (i.e. burial depths that exceed bioturbation depths) (Wheatcroft et al., 1997). Abandoned channel bends in lowland fluvial settings can present ideal settings for event scale sediment capture (Allen, 1965). However, the character of such sedimentary deposits is also dependent in part on local geomorphic and hydrologic conditions that control hydro-sedimentological connectivity to the river mainstem (Constantine et al, 2010, Toonen et al., 2012). One consequence of the morphology of this coupling can be the imposition of dynamic event magnitude thresholds as physical inundation and sediment entrainment barriers evolve with deposition or scour (Kleinhans et al., 2013). Such variable connectivity between the zone of deposition and fluvial sediment supply can impose significant complications to paleohydrologic interpretations of abandoned channel sediment deposits.

Although coastal and estuarine depositional environments have been used extensively to record long-term average sedimentation rates worldwide, there is relatively little scientific knowledge about how episodic sediment delivery functions in dry-summer subtropical estuaries (Rich and Keller, 2012). In this study, sediment cores collected from an abandoned river channel bend located in a small estuarine lagoon at the mouth of a coastal dry summer subtropical watershed in central coastal California were examined as potential records of episodic sediment delivery over the last ~ 50 years. The first study objective was to quantify rates of sediment deposition and evaluate their feasibility as a proxy for watershed sediment delivery. The second study objective was to relate deposition rates to hydro-climatic activity, suspended sediment discharge, records of time-synchronous individual disturbances, and local hydro-geomorphic conditions to parse out the most important factors contributing to stratigraphic characteristics (e.g. particle size distribution) and sedimentation rates. To this end we synthesized hydro-sedimentological results from the lower Salinas River first reported in Gray et al., (2014) and stratigraphic data and results and from its estuarine lagoon first presented in Watson et al. (2013) to better understand dry-summer subtropical episodic sediment delivery. Characteristics of lagoon sediment deposits were tested for dependency on water and sediment discharge characteristics. Results were then considered in the context of the drivers of changing sediment regimes in the Salinas River watershed.

BACKGROUND

Study Area

The Salinas River is the largest watershed and water source discharging to Monterey Bay, draining 11,605 km² of the Central Coast Ranges of California with a mean discharge (Q_{mean}) of 11.6 m³ s⁻¹ (Gray et al., 2015a). Originating in the Garcia Mountains, the Salinas River flows

north-northwest for 250 km toward the Salinas River Lagoon through a central trough of valley bottomlands flanked by the Santa Lucia and Gabilan Mountains to the southwest and northeast, respectively (Fig. 1). Previously the Salinas River drained into Monterey Bay in the vicinity of Elkhorn Slough, some 6 km north of the current position in the vicinity of the Salinas River Lagoon (Watson et al., 2013). Geologic substrate is primarily Mesozoic sedimentary rock and overlying Pleistocene to Holocene alluvium (Garcia and Mahan, 2009; Rosenberg and Joseph, 2009).

The regional climate is dry-summer subtropical. Most annual precipitation falls as rain originating from winter storms, and thus the ‘water year’ in this region is defined as running from October 1 of the previous year to September 30. The largest of these storms tend to occur during strong El Niño years when high sea surface temperature anomalies in the equatorial eastern Pacific increase the likelihood of moisture advection from the tropical western Pacific (Farnsworth and Milliman, 2003; Andrews et al., 2004). A strong precipitation gradient extends from the wetter SW ($\sim 100 \text{ cm yr}^{-1}$) to drier NE ($\sim 30 \text{ cm yr}^{-1}$) region of the Salinas River watershed due to orographic forcing (Farnsworth and Milliman, 2003) and the predominant S-SW impingement of storms (Andrews et al., 2004).

Figure 1. The Salinas River Lagoon study area. S1 refers to the lowest hydrologic gage on the Salinas River mainstem (USGS gage #11152500), and BGS is the Big Sur State Park atmospheric station of the National Weather Service. Aerial photograph from the USGS Earth Explorer (2017).

The hydro-sedimentological response of the Salinas River to this regional climatic regime is one of even greater extremes. For example, one finds increasing proportional differences between the maximum and minimum when comparing annual precipitation (P_{annual}), annual water yield (WY), peak annual discharge (Q_{peak}), and annual suspended sediment load (Q_{ss}) (Table 1). While maximum P_{annual} observed at the NOAA BGS station is 5 times (~ 0.7 orders of magnitude) greater than the minimum observed value, WY extrema differ by 3.5 orders of magnitude. Moving to event scale hydrological values, the peak annual discharge of the lower Salinas (Q_{peak}) varies by 4.3 orders of magnitude. As is typical of the small mountainous systems that drain the California Coast Ranges, the suspended sediment load of the Salinas River is extremely variable, with maximum annual Q_{ss} some 7 orders of magnitude greater than the minimum. This is indicative of the event driven nature of sediment flux from these highly dynamic systems, which have been shown to express infrequent, high magnitude episodes of effective sediment discharges from

infrequent, high magnitude storm events (Inman and Jenkins, 1999; Farnsworth and Milliman, 2003; Gray 2015b).

Table 1. Salinas River watershed hydrometeorological characteristics.

Descriptor	P_{annual} (cm yr ⁻¹)	WY (10 ⁶ m ³)	Q_{peak} (m ³ s ⁻¹)	$Q_{SS\ annual}$ (Mt yr ⁻¹)
Base Period	1931-2011	1931-2015	1931-2015	1969-2011
Mean	105.2	345.2	393.8	2.6
Minimum	37.2	0.7	0.1	0.0000018
Maximum	197.2	2178.3	2690.1	23.9
Max/Min (arithmetic)*	5.3	3024.1	21590.9	13164384.3
Max/Min (log₁₀)*	0.7	3.5	4.3	7.1

*unitless; P_{annual} data from the NOAA BGS station, hydrologic data from USGS gage ##11152500, sediment flux data from Gray et al. (2015b)

Indeed, the four water years with the greatest peak discharge events (1969, 1978, 1983 and 1995) were found to have produced ~ 70% of the total Q_{SS} over a 45-year period of sediment monitoring (1967-2011) in the lower Salinas River (Fig. 2; Gray et al., 2015b). The magnitude of these flood events ($1625\text{-}2690\text{ m}^3\text{s}^{-1}$, or ~ $140\text{-}230\text{ }Q_{mean}$) were found to correspond with a recurrence interval of 20 to 30 years (Gray et al., 2015a). The dependence of Salinas River flood flows on event scale rainfall intensities rather than annual or interannual precipitation totals is evident by the fact that the largest peak flows during this period often occurred the year after very low precipitation years (e.g. the flood flows of 1978 and 1995), and the water year of highest annual precipitation (1998) produced only a moderate peak discharge (Fig. 2). On further examination, Q_d records show that each large flood year was characterized by only one peak event with a $Q_d > 1000\text{ m}^3\text{s}^{-1}$, except for 1969, which contained the largest ($Q_d = 1992\text{ m}^3\text{s}^{-1}$) and fourth largest ($Q_d = 1512\text{ m}^3\text{s}^{-1}$) Q_d peak events of the period, the smaller of which was larger than the peak event of 1978 ($Q_d = 1121\text{ m}^3\text{s}^{-1}$). Each high flow year coincided with moderate strong El Niño conditions; 1983 was the strongest El Niño over this period and the storms that resulted in large lower Salinas floods that year also produced record waves and storm surges for the region (Storlazzi et al., 2000). The 1978 flood occurred the year after the Marble Cone Fire burned nearly the entire Arroyo Seco Watershed

(Warrick et al., 2012). Widespread flooding of the lower Salinas River occurred during all four peak discharge years, resulting in millions of dollars in damages to homes, agriculture and infrastructure (WEOP, 1995; MCWRA, 2017).

Figure 2. Discharge and precipitation time series data from the S1 gage and BGS station, with the four peak flood years highlighted.

Sediment Core Analyses

Three sediment cores of less than one meter in length were collected from the Salinas River Lagoon near the head of an abandoned channel bend of the Salinas River in 2007 using vibracoring techniques (Fig. 1; Watson et al., 2013). For one of these cores (SRL1, 40 cm depth) recent (late 20th - early 21st century) flood layers were identified and dated using a combination of stratigraphic analyses, chronologic indicators, and the peak discharge time series of the lower Salinas River

(Watson et al. 2013). Two additional sediment cores (SRE1 and SRE2) that exhibited the same stratigraphic sequences were collected <10m distant from SRL1 from the same abandoned meander channel.

All three cores were split lengthwise, photographed, x-radiographed, and their stratigraphy described. Cores SRL1, SRE1, and SRE2 were sub-sampled following lithological breaks (1-2.5 cm intervals) and sediments were analyzed for bulk density and particle size distribution. Bulk density was determined by extracting 1 cc subsamples of sediment which were dried at 60 °C for 24 hours and cooled to room temperature in a vacuum desiccator before being weighed on a four-place balance. Particle size distributions for mineral sediments were obtained by removing organic material through heated H₂O₂ pretreatment followed by deflocculation with sodium metaphosphate (Gray et al. 2010), and then run through a Beckman Coulter LS-230 particle size analyzer. The following descriptive statistics were computed using the full method of moments with GRADISTAv8 software (Blott and Pye, 2001): D_{10} , D_{50} and D_{90} (where for D_n , n% of the distribution has a smaller diameter). Aggregate particle size distribution descriptors for each deposit were formed as $D_{10} \text{ min}$ (minimum D_{10}), $D_{50} \text{ mean}$ (mean D_{50}) and $D_{90} \text{ max}$ (maximum D_{90}).

Core SRL1 was additionally analyzed for trace elements using an ICP-AES instrument, for Cs-137 activity using a Canberra GL2020RS low energy germanium planar gamma ray detector, and for pollen spectra and abundance as a tool to refine accretion rates (Cooper and Brush 1991; Watson et al. 2013). A core chronological model was developed for the cores based on Cs-137 activities, initially refined by peak total lead concentrations attributed to the end of leaded gasoline usage in 1974, and further refined by flood deposit alignment with the hydrologic record. Sedimentation rates were calculated as mass flux per unit area for each flood deposit, and inter-

flood period by multiplying the depth of accretion by the bulk density and dividing by the time period of accretion (assigning 1 year to each flood deposit). Pollen abundance in sediments was assessed by spiking subsamples with known quantities of lycopodium spores (Stockmarr, 1971), processing to remove extraneous materials and stain pollen grains, and then counted/identified at 400x magnification. Here we focus only on the total abundance of all pollen grains (C_{pollen}), and the ratio of wetland pollen (Chenopodiaceae + Poaceae, Cyperaceae + *Typha* + *Ruppia*) to abundant upland pollen types (*Quercus* + *Pinus* + Rhamnaceae).

Hydro-Meteorological Data and Analyses

Time series of hydro-meteorological data were compared to stratigraphic and sedimentological characteristics of the abandoned channel cores graphically through cumulative plots over the period of record and bivariate analysis with simple linear regression. Peak and daily discharge (Q_{peak} and Q_d , respectively) records from the lowest US Geological Survey gaging station on the Salinas River mainstem (USGS gage #11152500: Salinas River near Spreckels), referred to here as S1 (Fig. 1), were obtained for the period of 1968-2007 (USGS NWIS, 2017). National Weather Service monthly precipitation records from stations at Big Sur State Park (BGS) (Fig. 1), previously recognized as having the greatest correspondence with discharges in the Salinas River Watershed (Warrick et al., 2012), were compiled and corrected for gaps as per Gray et al. (2014). Estimates of annual suspended sediment flux from the lower Salinas River over the period of 1968-2007 were obtained from Gray et al. (2015b). The estimates used for this study were those accounting for non-stationary suspended sediment concentration – discharge behavior through multiple regression techniques that incorporated Q and antecedent hydrologic conditions as independent variables, and were corrected for daily discharge and log-transform bias (Gray et al., 2015a, b).

RESULTS

Flood Deposit Identification

Based on sediment stratigraphy and chronological control provided by down-core patterns in Cs-137 activity and bulk lead concentrations reported in Watson (2013), flood laminations were identified at 1-4 cm, 6-8.5 cm, 11-12 cm, and 13-17 cm, and assigned ages of 1995, 1983, 1978 and 1969 respectively (Watson et al. 2013). This depositional model for SRL1 was further confirmed by plotting down-core variations in wetland/upland pollen ratios and peak discharge at S1 (Fig. 3). Wetland/upland pollen minima were found to correspond to C_{pollen} minima found in discrete sediment layers at 1-4 cm, 6-8.5 cm, and 13-17 cm depths. Furthermore, at the 11-12 cm depth range moderately low wetland/upland pollen and C_{pollen} levels were found, along with an abundance of visible charcoal rendering the layer black in color, which corresponds to the range of Pb maximal abundance associated with the end of the leaded gasoline era of the 1970s found by Watson et al. (2013). It also corresponds to the timing of the 1977 Marble Cone Fire, which burned the entirety of the Arroyo Seco watershed, a major subbasin of the Salinas River (Warrick et al., 2012).

Stratigraphy

The same stratigraphic patterns were found in SLR1, SRE1 and SRE2, which differed only in the thickness of individual horizons, and the lack of one low accretion rate horizon in SRE1 (Fig. 3, Table 2). Briefly, each core was capped by a thin (0.5 to 1 cm thick) surface unit of peaty mud with numerous *Salicornia* roots representing deposition from 1996 to 2007, followed by a sequence of each flood deposit and intervening deposits of low accretion rates, with the exception of accretion during the 1970-1977 period, which was absent from SRE1. The texture of flood layers (a) 1995 and (b) 1983 were massive units of mud and silty fine sand, respectively. In

contrast, flood layer (c) 1978 was a charcoal rich clay unit, while (d) exhibited a coarsening upward sequence from very-fine sandy silt to silty fine sand, followed by fining upward to fine sandy silt.

Figure 3. Shared stratigraphic column for the Salinas Lagoon cores with depth increments specific to SRL1. See text for details on pollen and geochemical analyses. Q_{peak} time series from the Salinas River S1 gage. Shaded regions indicate identified flood deposits with corresponding date.

Table 2. Salinas River Lagoon abandoned channel sedimentation.

Period	Duration (yr)	Deposit Thickness (cm)			Sedimentation Rate (kg m ⁻² yr ⁻¹)		
		SRL-1	SRE-2	SRE-1	SRL-1	SRE-2	SRE-1
1996-2007	12	1.0	0.5	0.5	0.3	0.1	0.1
1995	1	3.0	6.5	6.0	28.8	62.4	57.6
1984-1994	11	2.0	1.0	0.5	1.7	0.8	0.4
1983	1	2.5	3.0	1.5	30.5	36.6	18.3
1979-1982	4	2.5	0.3	2.0	4.1	0.4	3.3
1978	1	1.0	0.8	0.8	7.3	5.4	5.4
1970-1977	8	1.0	1.0	0.0	1.0	1.0	0.0
1969	1	4.0	4.5	4.0	51.6	58.0	51.6

Relationships Between Sediment Deposit and Hydrometeorological Characteristics

The pattern of flood deposits found in SRL1, SRE1 and SRE2 corresponded to the four largest peak discharges in the late 20th to early 21st century accretionary period of the Salinas River

Lagoon (Fig. 2 and Fig. 3). Background sedimentation rates during non-flood events ranged from 0.1 to 4.1 kg m⁻² yr⁻¹, while flood deposit sedimentation rates ranged from 5.4 to 62.4 kg m⁻² yr⁻¹ (Table 2). Normalized cumulative times series plots revealed stronger indications of coherence between sediment deposition rates and peak event scale hydro-meteorological characteristics relative to annual scale summed variables (Fig. 4). Integrated across the entire period of accretion, Q_{SS} and Q_{peak} display the closest correspondence with sedimentation, with a notable departure toward the end of the record when sedimentation rates slow down despite relatively high Q_{SS} and Q_{peak} in the later part of the 1990s during an El Niño period. Patterns of annual WY correspond to the placement of jumps in sedimentation rate, but not relative magnitude. The time series of P_{annual} shows little correspondence to sedimentation rates, in part due to muted variability relative to sedimentation rate.

Figure 2. Plots of sedimentation (for all sediment cores, range shaded) and hydro-meteorological values from the Salinas River watershed, sequentially summed over the period of accretion and normalized to their respective total values.

Comparison of dated flood sedimentation rates with the hydro-meteorological record revealed that sedimentation rates scales with peak event (Q_{peak}) and peak event dependent

characteristics (*Peak Event Q_{ss}*), but not with annual scale lumped parameters (P_{annual} and WY) (Fig. 5, Table 3). Sedimentation rates generally increased with Q_{peak} , although the average sedimentation rate between the three cores was higher for 1969 than 1995, despite 1995 having the highest Q_{peak} (Fig. 5a). The strongest dependency was found between sedimentation rate and *Peak Event Q_{ss}* (Fig. 5b). This may be because 1969 had two large flood events (Fig. 3), which was not captured in the Q_{peak} record, but was reflected in the estimation of *Peak Event Q_{ss}* , which included both 1969 events. The lack of a relationship between sedimentation rate and WY (Fig. 5c) reflected the importance of large discharge events in both the production of Salinas River suspended sediment and the inundation of the depositional zone. A slightly positive, but non-significant relationship between sedimentation rate and P_{annual} is likely a result of the fact that large flood producing storms are somewhat more likely to occur during years with high P_{annual} magnitudes (Fig. 5d) (Farnsworth and Milliman, 2003).

Figure 3. Sedimentation rates for identified flood deposits from each sediment core plotted against (A) peak annual discharge, (B) peak event suspended sediment discharge, and (C) annual water yield from the lower Salinas River, and (D) annual precipitation at the BGS station.

Table 3. Linear relationships between stratigraphic and hydrologic characteristics.

Stratigraphic Variable	Hydrologic Variable	Slope	Intercept	R^2	P -value
Sedimentation rate	WY	-4.0E-05	3.51	1.0E-04	0.97
Sedimentation rate	Q_{SS}	0.35	0.23	0.78	1.3E-04
Sedimentation rate	P_{peak}	0.17	1.59	0.03	0.61
Sedimentation rate	P_{annual}	0.02	-0.33	0.05	0.50
Sedimentation rate	Q_{peak}	4.0E-03	-4.92	0.67	1.2E-03
D_{10min}	Q_{peak}	-0.01	31.78	0.18	0.17
D_{50mean}	Q_{peak}	-0.04	129.89	0.11	0.28
D_{90max}	Q_{peak}	-6.0E-03	172.59	3.0E-04	0.96

Aggregate particle size distribution metrics for each flood deposit were compared against Q_{peak} as a proxy for the peak hydrodynamics of event flood flows (Fig. 6, Table 3). As expected from visual inspection of the stratigraphic column (see Fig. 2) no significant monotonic

relationship was found, and sediment texture appeared to be unrelated to the magnitude of the depositing discharge event.

Figure 4. Particle size distribution metrics from the Salinas River Lagoon abandoned channel flood deposits plotted against peak annual discharge at gage S1.

DISCUSSION

Sedimentation of the abandoned Salinas River Lagoon channel was dominated by infrequent, high magnitude ($Q_{peak} > 1500 \text{ m}^3\text{s}^{-1}$ or $Q_d > 1000 \text{ m}^3\text{s}^{-1}$, i.e. $\sim 100\times Q_{mean}$) discharge events. Sedimentation rates scaled with event scale water and sediment flux magnitudes, but the particle size distribution of the resultant deposits did not. Flood deposits were interspersed with relatively long (decadal scale) periods of more moderate flows producing little accretion, despite more water discharged in sum during these periods of quiescence. This pattern of sedimentation mirrors the sediment regime of the Salinas River, where the magnitude-frequency behavior of water and suspended sediment fluxes diverge (Gray et al., 2015b). Thus, the investigated sediment deposits have potential to serve as proxies for watershed scale sediment delivery, with important caveats related to local effects and the potential role of scour.

Flood sedimentation rates scaled with Q_{peak} and peak event Q_{ss} , yet the particle size distribution of flood deposits were not consistently related to event magnitudes. Both of these phenomena are likely the result, at least in part, of relatively low hydro-sedimentological connectivity to the main channel. Well-developed plug bars appear to almost completely obscure the upstream and downstream entrances to the mouth of the abandoned channel (see Fig. 1), which is elevated about 1 m above the tidal wetlands fringing the main channel. The main channel of the Salinas River itself remains closed to the ocean except for a combination of natural and artificial breaches timed with high discharge events (Watson, 2001; Watson, et al, 2013). These factors seem to have resulted in a depositional setting that effectively traps sediment from large floods (20+ year return interval; $Q_{peak}/Q_{mean} \geq 100$), receives very little sediment from lesser fluvial flows, and perhaps no sediment from tidal exchange, with the potential exception of time periods immediately after large discharge events.

The same geomorphic conditions likely interact with fluvial controls to result in the lack of correlation between flood deposit particle size distribution and flood event magnitudes. The super-elevation of the alluviated abandoned channel and plug bar at its upstream entrance would be expected to act as an effective block of Salinas River mainstem bedload entrainment, and could also serve to block coarser fractions of the suspended load that display strong depth dependence. This is supported by previous work of Watson et al. (2013), which reported deeper sediments deposited in the SRL1 core that corresponded in particle size distribution and stratigraphic character with flow-through/channel bed deposits from a time when the abandoned channel was more explicitly connected to the Salinas River mainstem during more generally open river mouth conditions. Under the subsequent conditions of a generally closed Salinas River mouth, and a more hydro-sedimentologically disconnected abandoned channel, the geomorphic selection of

entrainment waters, and their impact in terms of sediment supply characteristics would depend on fluvial discharge characteristics, as well as the changing conditions of the mouth of the Salinas River, and tidal stage/storm surge conditions after the mouth opened. Furthermore, Gray et al. (2014) found that on average the particle size distribution of suspended sediment transported in the lower Salinas River undergoes cycles of fining and coarsening with increasing discharge magnitude; notably coarsening from ~ 1 to $10 Q_{mean}$, and then fining by $100 Q_{mean}$. This is evidence that the fluvial supply of suspended sediment to the abandoned channel during effective floods does not display the coarsening trend that is traditionally expected through hydraulic/entrainment considerations alone (i.e. shear stress scaling with discharge in confined channels).

Thus, the wide range of particle size distributions found in the flood deposits seem to reflect the interaction between a rather static suspended sediment particle size distribution and geomorphic and hydrodynamic processes that impose both relatively static (depth barrier) and dynamic (backwater/tidal) selective processes on the particle size of sediments entrained and deposited into the abandoned channel. Gray et al. (2016) proposed a modification of fluvial channel alluviation architecture for mixed fluvial/tidal settings to incorporate tidal rhythmites (i.e. finely laminated, fine-grained sediments) interspersed with event based fluvial deposits. However, this model applies to cases where the abandoned channel remains directly hydro-sedimentologically connected to tidal forcings through at least its downstream entrance as a tidal slough. In this case dynamic hydro-sedimentological connectivity imposes a variable local condition that in turn drives variable particle size distributions in the deposited sediments, despite capturing discrete deposits from large events.

What can we learn about past fluvial sedimentary regimes from the deposits they leave behind? The answer to this fundamental question of paleo-hydrology/sedimentology, here and

elsewhere, remains a cautionary, ‘It depends.’ Small mountainous rivers experiencing episodic precipitation regimes producing highly episodic fluvial sediment transport may be expected to translate to event driven sedimentation, as we found here. Many studies across a range of physiographic and climatic settings have pointed toward the importance of fluvial sediment supply in controlling the sedimentation rate and accretion of estuarine wetlands (Krone, 1962; Dyer, 1989, van Rijn, 2005; Cuvilliez et al., 2015; Boyd et al, 2017) and a few have found catchment controls on broader estuarine geomorphology under Mediterranean climatic regimes (Rich and Keller, 2012; Estrany and Grimalt, 2014). While the large sediment transport events in this study were characterized using rating curve estimates for the lower Salinas River that incorporate the role of antecedent conditions, the possibility remains that the sediment loading of these floods may have significantly differed from our estimates.

Cursory investigation of spatially distributed erosion thresholds in the region has revealed what are likely major differences in dominant erosional processes throughout the watershed. A desktop GIS analysis of landscape erosion thresholds (Dietrich et al., 1993; Montgomery and Dietrich, 1994) was assembled using public data on catchment topography, soils, and precipitation to frame the erosional context of the catchment setting. This approach utilizes simple steady-state erosion threshold equations coupled with spatially distributed estimates of contributing area and slope, soil erosivity and hydrologic characteristics, and average winter precipitation values to develop rough estimates of the spatial distribution of dominant erosion processes. The results of this analysis suggest that the Salinas River watershed as a whole is likely dominated by sheetwash erosion, while the Arroyo Seco subcatchment is likely dominated by shallow landsliding. Thus, even if watershed sediment supply is driven by sheet wash erosion on the whole, the proximity and extent of a shallow landsliding dominated region closer to the river mouth means that lower

Salinas Sediment fluxes could depart radically from rating curve estimates, particularly when disturbance events are focused on the Arroyo Seco subcatchment. While mainstem Salinas River vs. Arroyo Seco sediment provenance has not been found to impact sediment dynamics in the lower Salinas on average (Gray et al., 2014), large magnitude disturbances, such as the sequence of wildfire and intense precipitation that resulted in the Arroyo Seco doubling the lower Salinas suspended sediment load after the 1977 Marble Cone Fire (Warrick et al., 2012), may drastically alter sediment loading at the event scale.

However, even systems experiencing well characterized highly variable, event driven sediment supply do not necessarily record event driven depositional signatures. Sedimentation rates in some estuarine wetlands have been found to be largely controlled by local issues of accommodation space, even under increasing sediment supply regimes (e.g. Packenham, 2010), while others have recorded sedimentation rates sensitive to changes in sediment supply and effective event frequency (Elliott et al., 2015; Avnaim-Katav et al., 2017). The difference between cases where strongly episodic sediment delivery result in episodic versus relatively steady sedimentation rates arise from differences in depositional settings as well as the temporal resolution of the sedimentary analysis/sedimentary records. Mixed fluvial/tidal depositional environments vary widely in their degree of hydro-sedimentological connectivity, as driven by both the planform position of the depositional site relative to distributary/drainage structures, and elevation (Temmerman et al., 2004). Sub-aqueous settings such as estuarine settling basins may be sensitive to initial event-based sediment deposition, but are generally more prone to tidal and wave driven rework and bioturbation that can compromise event signatures (Dott, 1983; Wheatcroft and Drake, 2007, Achete et al., 2016, Carlin, 2016). Higher elevation and or distal sites are further removed from fluvial sediment delivery, and may not receive almost any direct

tidal influence on the delivery/redistribution of sediments. This appeared to be the case in the lower Salinas abandoned channel, as evidenced by its lack of tidal rhythmites. However, low elevation estuarine wetlands regularly experiencing tidal inundation are subject to both increased connectivity to fluvial sediment/water fluxes, as well as tidal delivery/redistribution of sediments, even in cases of interior marshes (Palinkas and Engelhardt, 2015). This high degree of connectivity can result in relatively steady sedimentation rates due to accommodation space limitation and tidal redistribution (Temmerman et al., 2014).

Yet, rework and erosion of fluvial sediment deposits are not limited to low elevation settings with high tidal and/or fluvial connectivity. Antecedent deposits in abandoned channels and floodplains, such as the case examined here, can also be subject to erosion from the same events that subsequently result in net fluvial sediment deposition. Truncation of individual flood deposits through scour from subsequent events may play a role in the depositional patterns found in this abandoned channel alluviation. While the evidence presented here cannot eliminate this possibility, a preponderance of high pollen concentrations and wetland/upland pollen ratios found between most flood deposits support an interpretation of multiple small scale inundations between flood events producing deposits with lower sedimentation rates. A more likely case for scour would be the flood events themselves truncating the ‘quiescent’ periods of low sedimentation. Indeed, flood scour may have further depressed the low sedimentation net rates for these periods. In core SRL1 the 1978 flood may have completely eliminated the 1970-1977 depositional period and potentially scoured into the 1969 flood.

Finally, the temporal scale of focus relative to the effective time scale of sediment delivery and sediment rework remains an important consideration. All accommodation space limited depositional settings will eventually record a signature of the rate of accommodation space supply

if averaged over time periods that approach the scale of accommodation space development (Cattaneo and Steel, 2003). The case of the Salinas River lagoon further illustrates the utility of abandoned channels in particular, and channel adjacent lowlands in general, as records of past hydro-meteorological conditions, with the caveat that such records are also very dependent on interactions with local geomorphic conditions.

CONCLUSIONS

The lower Salinas River lagoon abandoned channel alluviated in an estuarine setting with no evidence of a tidal signature, a high discharge threshold for effective sedimentation, and no scaling of particle size distribution with discharge event magnitude. Here we have a case of abundant accommodation space and limited hydro-sedimentological connectivity selecting for a record of high magnitude fluvial deposits, yet colluding with relatively static fluvial suspended sediment particle size distributions and uncertain/variable backwater/tidal connectivity issues to produce deposit textures that do not scale with discharge magnitude. Unresolved issues of potential flood event scour may have depressed apparent sedimentation rates during inter-flood periods, accentuating the role of event driven sedimentation. The utility of such deposits as sediment delivery proxies may also be limited by the relatively short duration of favorable local conditions – in this case only spanning the historical record. Further investigation of the role of the processes controlling abandoned channel deposits across mixed fluvial/tidal settings displaying a range of connectivity and fluvial/tidal dominance levels is essential for shedding light on abandoned channel alluviation in these settings, and exploiting them as records of local and basin scale geomorphic and hydro-meteorological change.

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