

The Role of Sediment Dynamics for Inorganic Accretion Patterns in Southern California's Mediterranean-Climate Salt Marshes

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Abstract Salt marsh resilience to sea-level rise depends on marsh plain elevation, tidal range, subsurface processes, as well as surface accretion, of which suspended-sediment concentration (SSC) is a critical component. However, spatial and temporal patterns of inorganic sedimentation are poorly quantified within and across *Salicornia pacifica* (pickleweed)-dominated marshes. We compared vertical accretion rates and re-examined previously published suspended-sediment patterns during dry-weather periods at Seal Beach Wetlands, which is characterized by a mix of *Spartina foliosa* (cordgrass) and pickleweed, and for Mugu Lagoon, where cordgrass is rare. Mugu Lagoon occurs higher in the tidal frame and receives terrigenous sediment from an adjacent creek. Feldspar marker horizons were established in winter 2013–2014 to measure accretion. Accretion rates at Seal Beach Wetlands and Mugu Lagoon were 6 ± 0.5 mm/year (mean \pm SE) and 2 ± 0.3 mm/year. Also, the estimated sediment flux (g/year) across the random feldspar plots was 3.5 times higher at Seal Beach Wetlands. At Mugu Lagoon,

accretion was higher near creeks, although not statistically significant. Dry-weather SSC showed similar concentrations at transect locations across sites. During wet weather, however, SSC at Mugu Lagoon increased at all locations, with concentrations decaying farther than 8 m from tidal creek edge. Based on these results from Mugu Lagoon, we conclude accretion patterns are set by infrequent large flooding events in systems where there is a watershed sediment source. Higher accretion rates at Seal Beach Wetlands may be linked to lower-marsh elevations, and thus more frequent inundation, compared with Mugu Lagoon.

Keywords Sea-level rise · Salt marsh accretion · Suspended-sediment concentration · Mediterranean climate · *Salicornia pacifica* · *Spartina foliosa*

Introduction

Salt marshes provide a myriad of ecosystem services, such as trapping pollutants, storing carbon, and providing critical breeding habitat for endangered birds (Massey et al. 1984; Powell 1993; Costanza et al. 1997; Chmura et al. 2003; Barbier et al. 2010). Despite their intrinsic and utilitarian values, these resources are threatened by past and current habitat conversion, climatic factors, and future rates of relative sea-level rise (Kirwan et al. 2010; National Resource Council 2012; Kirwan and Megonigal 2013). Global sea-level rise could cause salt marshes to migrate landward and/or could lead to shifts in habitat types. Some salt marshes with high accretion potential will persist under high rates of sea-level rise (Kirwan et al. 2016), but because local processes are variable between sites, local site data is needed to predict resilience (Webb et al. 2013). Understanding and mitigating the impacts of sea-level rise is difficult because fine-scale elevation changes may cause drastic shifts in

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inundation patterns, sedimentation and plant abundance, distribution, and productivity across marshes (Kirwan and Guntenspergen 2012; Janousek et al. 2016). If salt marshes cannot keep pace with sea-level rise, the availability of transgression habitat will play a key role in the future persistence of these habitats (Schile et al. 2014), but in the highly urbanized region of southern California, transgression habitat is limited. In anticipation of sea-level rise effects, and assuming transgression habitat will continue to be limited, vulnerability assessments can inform management actions within the current extent of salt marsh. These assessments include shoreline stabilization, marsh drainage restoration, and elevation augmentation, which can mitigate future salt marsh collapse (Wigand et al. 2015).

Current tide range and sediment supply affect a salt marsh's ability to keep pace with sea-level rise (Raposa et al. 2016). Mineral deposition in marshes is often an episodic process, with strong linkages to storm magnitude and frequency (Reed 1989; Cahoon et al. 1996; Turner et al. 2006). Southern California coastal marshes differ from marshes in many other parts of the world due to the highly seasonal winter precipitation regime of the Mediterranean climate. Almost all precipitation and storm events occur in the winter months and often are delivered in a few, larger storm events during atmospheric rivers or strong El Niño years (Warrick and Farnsworth 2009; Dettinger 2013). Future climate change predictions in the southwest USA suggest that the region may experience more frequent and intense droughts (MacDonald 2010; MacDonald et al. 2016). Therefore, we need to understand vertical accretion and associated sediment dynamics in salt marsh ecosystems during extended periods of dry weather, as well as during storms, in order to inform future management actions for salt marshes.

These events may have different impacts on sedimentation and accretion depending on tidal elevation. For example, Cahoon et al. (1996) observed that low-marsh zones were accreting more than high-marsh zones during storm-driven stream flows in a salt marsh in the Tijuana Estuary. Other studies have found that high rates of accretion in natural and restored portions of Tijuana estuary salt marshes are mainly due to sediment deposition from storms (Weis et al. 2001; Callaway and Zedler 2004; Wallace et al. 2005). Similarly, Mugu Lagoon has experienced loss of open-water habitat due to a large sediment deposition during El Niño events (Onuf 1987). However, some Mediterranean-climate salt marshes in other regions, such as Venice Lagoon, Italy (Day et al. 1998), San Francisco Bay Area, California (Callaway et al. 2012), and Ebro Delta, Spain (Calvo-Cubero et al. 2013), have been highly modified due to agriculture and urban uses, and consequently have highly variable sedimentation rates. Watershed-level comparisons in non-Mediterranean-climate zone marshes show that watershed sediment availability is a key component of future resilience to accelerated sea-level rise (Day et al. 2011).

Within the marshes, vegetation structure can also play a role in altering flows and consequently trapping sediment and reducing

erosion on the marsh plain (Boorman et al. 1998). Results like these are useful for understanding intra-marsh elevation differences in the face of sea-level rise; however, a better understanding of inter-marsh differences is useful for comparing watershed-level effects, and ultimately management of isolated tidal salt marshes, which are common in the topographically isolated Pacific Coast. Large-scale models such as Sea-Level Affecting Marshes Model (SLAMM) have predicted catastrophic effects on a variety of salt marshes because they apply static, regional parameters to individual sites that are shaped by different processes (Kirwan et al. 2016). Site-specific differences are apparent in southern California, where recent short-term comparisons of surface elevation change between Seal Beach Wetlands (449 days) and Mugu Lagoon (664 days) show that the low salt marsh at Seal Beach Wetlands (−1.2 mm/year) is losing elevation faster than the low salt marsh at Mugu Lagoon (1.6 mm/year) (Rosencranz et al. 2016).

Conceptually, these elevational patterns are determined by the elevation of the salt marsh plain, tidal range, subsurface organic accretion, erosion, as well as surface accretion and suspended-sediment concentration (Morris et al. 2002; Wallace et al. 2005; Swanson et al. 2013). Within salt marshes, these patterns are spatially variable. Previous research in marshes of different climates and different vegetation zones has indicated a decline in sediment deposition from the tidal creek edge to the interior (Reed et al. 1999; Christiansen et al. 2000; Moskalski and Sommerfeld 2012). Here, we address the question of how much spatial variability in inorganic sediment deposition related to surface morphology and channels is apparent in two southern California salt marshes. Specifically, we ask (1) how critical are wet and dry-weather periods in the timing and magnitude of accretion, and (2) how do surface morphology and channels impact the spatial variability of mineral sedimentation and overall salt marsh evolution? Answering these questions can aid in assessing the vulnerability of salt marshes to future sea-level rise and extreme events.

Salt marsh zonation patterns of southern California are unique compared with other North-American salt marshes because they are dominated by pickleweed, and may only have cordgrass in low elevations and/or along tidal creek edges. Spatial zonation patterns are due to the effects of inundation patterns (Zedler 1982; Zedler et al. 1999). While cordgrass occurs in lower elevations, pickleweed and other shrubby halophytes like salt grass (*Distichlis spicata*) occur in the higher elevations of the salt marsh zones (Zedler et al. 1986). Episodic and infrequent storm events may induce rapid habitat conversion of pickleweed to cordgrass by increasing the frequency and depth of inundation (Zedler 1983). Conversely, rapid sedimentation can increase elevations, facilitating cordgrass colonization of exposed mudflat and pickleweed domination of desiccating cordgrass patches (Ward et al. 2003). Thus, fine-scale sediment deposition patterns play an important role in the characteristic zonation of southern California salt marshes, as well as resilience to sea-level rise.

Our study compared the relationship between vertical accretion and suspended-sediment concentrations in Seal Beach Wetlands, which has a mix of pickleweed and cordgrass, and Mugu Lagoon, where cordgrass is almost entirely absent. Our objectives were to determine: (1) short-term salt marsh surface accretion rates for these two common types of southern California salt marshes; (2) the spatial patterns of accretion and suspended-sediment concentrations within and across sites; and (3) the impact of wet and dry weather, during a drought period, on sedimentation patterns. Studies like ours will improve understanding of spatial patterns of suspended sediment and vertical accretion for Mediterranean-climate salt marshes, which are often not dominated by cordgrass (Zedler et al. 1999; Bonin and Zedler 2008) compared with more frequently studied cordgrass marsh types (i.e., temperate marsh types), to help determine regional patterns of resilience to sea-level rise in a more arid climate.

Methods

Study Sites

The Central Basin of Mugu Lagoon

Mugu Lagoon is located within Naval Base Ventura County Point Mugu (34° 06' N, 119° 05' W) and is part of a branched estuary with three open-water basins bordered by approximately 380 ha of salt marsh encompassing a network of tidal channels and lower-order creeks (Fig. 1). Our study focused on an approximately 112 ha in the central portion of the estuary. Muted tidal ranges may impact inundation/deposition patterns, but at our study sites the ranges are relatively robust. Mean High Water (MHW) is 1.39 m measured at the mouth of the estuary (Thome et al. 2016). Predicted maximum tide range was 2.6 m for 2013 (Mugu Lagoon Ocean Pier; http://tidesandcurrents.noaa.gov/tide_predictions.html). The site is one of the least impacted regions of the lagoon and lies along a dendritic tidal creek approximately 1.1 km in length (Fig. 1). Tidal creeks are typically bordered by pickleweed and fleshy jaumea (*Jaumea carnosa*) in the lower elevations and salt grass in the higher elevations. There is also an undeveloped upland transition zone, which is rare for the southern California region because of high-density coastal urbanization.

Mugu Lagoon lies at the base of the Calleguas Creek watershed, which has been altered significantly due to human activities (Sheng and Wilson 2009; Beller et al. 2011). Historically, Calleguas Creek was only connected to Mugu Lagoon via shallow sloughs and sheet flows during heavy rains. Today, the creek drains a 64,231 ha watershed—measured at USGS stream gage located 9 km upstream from Mugu Lagoon (Hydrologic Unit Code 18070103; <http://waterdata.usgs.gov/nwis>). The creek is characterized by

perennial low freshwater flows and low concentrations of sediment in Calleguas Creek during dry weather due to agricultural irrigation, urban runoff, and discharge from an upstream wastewater treatment plant. Large winter storms can greatly increase discharge and suspended-sediment concentrations (Onuf 1987).

Seal Beach Wetlands

Also located within a navy base (Naval Weapons Station Seal Beach) and of similar size to Mugu Lagoon, the Seal Beach Wetlands (Seal Beach Wetlands) (34° 44' N, 118° 05' W) encompass approximately 390 ha of salt marsh (Fig. 1). Our study focused on an approximately 206 ha, excluding major tidal creeks and mudflats. Mean High Water (MHW) is 2.06 m measured at Station 9410680 Long Beach Terminal Island, CA (<http://tidesandcurrents.noaa.gov/>). Predicted maximum tide range at this tide gage in 2013 was 2.7 m. In Seal Beach Wetlands, tidal creeks are typically bordered by cordgrass. In contrast to Mugu Lagoon, where upland transition zone is present and the marsh remains connected to a terrestrial watershed, Seal Beach Wetlands is surrounded by extensive suburban development beyond the boundaries of the Naval Station and has no direct link to a terrestrial sediment source (e.g., creek or river). Within the Naval Station there are adjacent agricultural and upland ecosystems.

Historically, Seal Beach Wetlands existed in one of the largest contiguous valley plain watersheds in southern California, receiving episodic storm flows and sediment from the meandering Santa Ana and the San Gabriel Rivers (Grossinger et al. 2011). Both rivers existed as braided channels and shifted paths during major flooding events. In response to flood damage between the late nineteenth and early twentieth centuries, the Santa Ana and San Gabriel rivers were channelized for flood control purposes, and today Seal Beach Wetlands exists in one of the most extensively urbanized basins in southern California (Brownlie and Taylor 1981; Stein et al. 2007). Five flood control channels—Bolsa Chica, Anaheim-Barber City, Westminster, East Garden Grove Wintersburg, and Ocean View Channel—drain 23,237 ha of urban landscapes into Anaheim Bay but not directly into Seal Beach Wetlands (Appendix). Flood control channels like these may result in reduced terrigenous sediment to estuaries. Specifically, 73% of sediment reductions have occurred in urban rivers (e.g., watersheds of Seal Beach), with only a 20% reduction of sediment in the Transverse Range (e.g., watershed of Mugu Lagoon) (Warrick and Farnsworth 2009).

Estimates of Salt Marsh Elevation

Digital elevation models were used to estimate relative differences in elevation between marsh sites (DEM; 2009–2011 California Coastal Conservancy Lidar Project: <https://data.noaa>

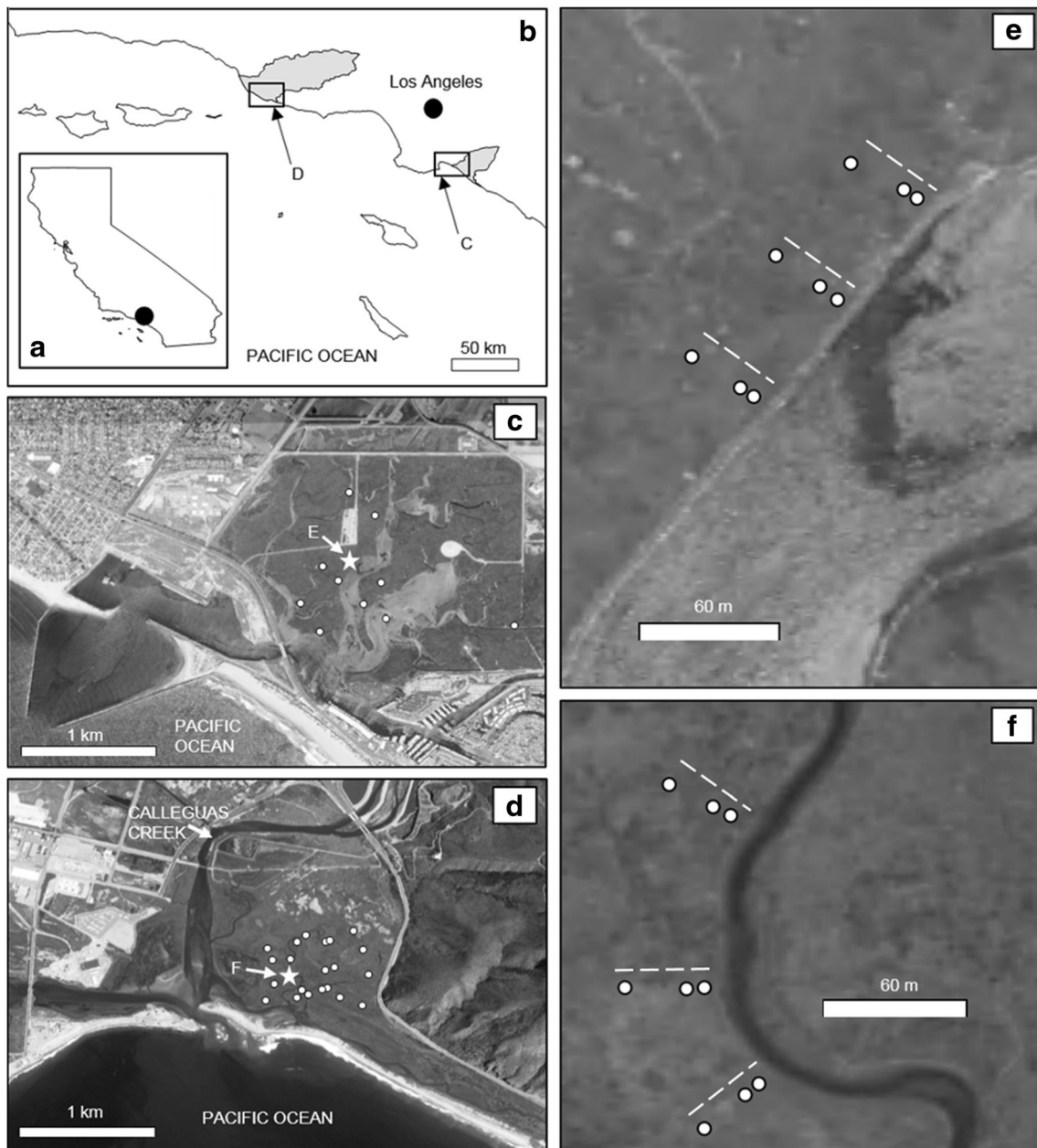


Fig. 1 Regional map showing approximate size and location of watersheds (a, b; source: <http://nationalmap.gov/viewer.html>) and maps of Seal Beach Wetlands National Wildlife Refuge (Seal Beach Wetlands; c) and the central basin of Mugu Lagoon (d). White circles in (c) and (d) show singles or pairs of independent feldspar markers sampled at Seal Beach Wetlands ($n = 20$) and Mugu Lagoon ($n = 41$) that were randomly distributed throughout both marsh footprints; white stars show location of

transects, while right column maps at Seal Beach Wetlands (e) and Mugu Lagoon (f) show locations of transects, where adjacent plots were at 3, 10, and 30 m from the edge of a tidal creek. Dashed white lines show approximate fixed-point sampling location for suspended-sediment concentrations which were established at 0, 1, 2, 3, 5, 8, 10, 15, 22, and 31 m from the edge of the major tidal creeks (Rosencranz et al. 2016)

<http://nationalmap.gov/viewer.html>; vertical datum: North American Vertical Datum of 1988 (NADV88)). These data were uncorrected for vegetation interference. All of our sampling locations were overlaid on the DEM in ArcMap 10.2.1, and elevations were obtained using the point extract values to points tool. Elevation statistics were calculated using pivot tables in Microsoft Excel.

Vertical Accretion

To assess within- and between-marsh accretion variability, 50 feldspar marker horizons (Cahoon and Turner 1989) were poured in vegetated areas in each wetland at Mugu Lagoon and Seal Beach Wetlands from 21 December 2013 to 2 January 2014 (Fig. 1). Plot locations were determined using

a random point generator (geomidpoint.com) within sections of a 5 × 5-m grid overlay on an aerial image of each wetland (earth.google.com).

In order to capture spatial variability within the salt marshes, as well as sedimentation patterns from storm and over marsh sediment deposition, we re-sampled three replicate transects of feldspar at 3 m, 10 and 30 m from the edge of tidal creeks at Mugu Lagoon and Seal Beach Wetlands (Fig. 1); plots that had been established and sampled once in a previous study by Rosencranz et al. (2016). Transect plot locations were poured within the same timeframe as the randomly selected marker plots. Locations were determined in the field, with transects at least 50 m apart. Each plot was treated as an independent sample.

To establish the feldspar plots, we sprinkled 1200–1600 mL of dry Custer Feldspar clay within the perimeter of a 0.5-m by 0.5-m quadrat, shaking the vegetation thoroughly to settle the feldspar. Corners of the plots were marked with gray PVC pipe. Because we expected some plots to be lost due to erosion and bioturbation (Cahoon and Turner 1989), each sampling location had two adjacent, independent 0.5-m by 0.5-m plots (Fig. 1).

We sampled marker plots using a plug extraction method suitable for drier soils (Cahoon et al. 1996). The sampling method consisted of visually surveying the adjacent plots at each sampling location to see if any feldspar was exposed. If feldspar was visible in any area of the plot, we recorded accretion as zero. If the plot was covered by sediment (i.e., no feldspar was visible), we carefully extracted an approximately 3 × 3 × 6 cm plug with a serrated kitchen knife, measuring the newly formed sediment layer on each side of plug with a ruler or calipers to the nearest millimeter. Annual accretion rates (AR; mm/year) were calculated using the following equation, where AM is measured accretion and L is age of plot in days:

$$AR = AM / \left(L * \frac{1 \text{ year}}{365 \text{ day}} \right) \quad (1)$$

Standard error (SE) for mean accretion rates was also calculated. If more than 1 mm accretion had occurred on the top of the plug, approximately 1 cm³ of recently accreted material was separated carefully from sediment layer above the feldspar, to avoid causing additional compaction; and the estimated 1 cm³ sediment volume was measured precisely using a syringe tube for further analysis. For bulk density, the 1-cm³ sample was dried at 105 °C for 24 h in a drying oven, while percent organic matter (OM) was determined by combusting the dried sample for 4 h at 550 °C in a furnace (Heiri et al. 2001). We recovered and sampled 41 of the 50 random horizon markers at Mugu Lagoon on 13 and 15 February 2015. In one plot, feldspar was not observed, while eight additional plots were not recovered (i.e., plot stakes may have been lost

or removed). Of the 41 random locations where sufficient accretion was observed, 27 independent surface samples were collected and analyzed in the laboratory. Also at Mugu Lagoon, we recovered and sampled eight of the nine transect horizon markers on 13 February 2015. Both plots at one location at 3 m from the tidal creek edge had disappeared and were likely eroded away, were disturbed by bioturbation, or were too deep to recover with the plug method; therefore, at 3 m, 10 m, and 30 m sample sizes were unequal ($n = 4$, $n = 6$, and $n = 6$, respectively). Of the 16 plot locations where accretion was observed in transects, 12 surface samples were collected and analyzed in the laboratory. Due to low accretion, we were unable to collect surface samples from one of the three transects. In those cases, no calculations of bulk density or percent organic matter were made.

At Seal Beach Wetlands, we recovered and sampled 20 of the 50 random horizon markers on 14 and 27 February 2015. Of the 20 random locations where accretion was observed, 17 surface samples were collected and analyzed in the laboratory. Also at Seal Beach Wetlands, we recovered and sampled all of the nine transect horizon markers on 27 February 2015.

Based on mean bulk density (BD; g/cm³) and mean accretion rates (AR; mm/year), we could estimate sediment fluxes (Q ; g/year) for a 0.25-m² plot (P) with the following equation:

$$Q = AR * P * BD \quad (2)$$

There are three models typically used to estimate BD from OM or loss on ignition (LOI; g/g). Morris et al. (2016) used a power function, power function with intercept, and an ideal mixing model to evaluate the relationship of BD to LOI. Since we were evaluating a narrow range of LOI and BD values for each site, and we were interested in comparing differences between sites, we used linear regression to calculate coefficient of determinations of bulk density to organic matter. We also calculated coefficient of determinations from the linear regression of mineral and organic accretion against total accretion to examine the statistical relationships between total vertical accretion and mineral and organic matter contributions.

Meteorological and Runoff Data

Daily measurements of precipitation for Seal Beach Wetlands were retrieved from the California Irrigation Management Information System (CIMIS) site no. 174 (<http://ipm.ucanr.edu/WEATHER/index.html>), which is 7 km north of the site. Daily measurements of precipitation for Mugu Lagoon were retrieved from CIMIS site no. 156, located approximately 17 km northwest of the site. Instantaneous creek discharge measurements (m³/s) from Calleguas Creek were obtained from a stream gage located

9 km upstream from Mugu Lagoon (Hydrologic Unit Code 18070103; <http://waterdata.usgs.gov/nwis>).

Suspended-Sediment Concentration

Sediment delivery by tidal creeks was examined by collecting suspended-sediment samples using a modified single-stage water sampler (Inter-Agency Committee on Water Resources Subcommittee On Sedimentation 1961) at 0, 1, 2, 3, 5, 8, 10, 15, 22, and 31 m perpendicular to the edge of the major tidal creeks; suspended-sediment concentration sampling methods and data were originally published in Rosencranz et al. (2016). Sample bottles were 0.25 L and were deployed during flood tides from January to March 2014 along three replicate transects at Mugu Lagoon and Seal Beach Wetlands (Fig. 1) parallel to the feldspar transects. At Mugu Lagoon, we sampled dry-weather suspended-sediment concentrations on 28–31 January 2014 on four consecutive flood tides, which occurred after a prolonged dry-weather period. Because of different tide heights and weather conditions during each day, each sample was treated as independent. Also at Mugu Lagoon, on 28 February–3 March 2014, we sampled suspended-sediment concentrations on four flood tides, which occurred during a wet weather period, which included any rain. At Seal Beach Wetlands, we sampled dry-weather suspended-sediment concentrations between 1 January 2014 and 3 February 2014, on ten consecutive flood tides, all of which occurred after a prolonged dry-weather period. No wet-weather suspended-sediment concentrations were sampled at Seal Beach Wetlands. Since not all samplers were filled during each sampling period, which decreased sample sizes for some interior sampling locations, we omitted data from all except three sampling events. In the sampling events, we retained for this study all samplers filled during each sampling event.

During a sampling event, samplers filled rapidly and represent an instantaneous suspended-sediment value. Lab methods followed U.S. Environmental Protection Agency (1971) protocols. Blank glass fiber filters were washed with distilled water and dried for 1 h at 103–105 °C, then cooled in a desiccator. The entire sample was passed through the clean pre-weighed filter using a vacuum hose filtration setup. Samples were dried at 103–105 °C for 1 h, cooled in a desiccator, and weighed to the nearest milligram. Samples were dried at 103–105 °C for another 20–30 min, cooled in a desiccator, and re-weighed to confirm that no additional mass loss had occurred. Glass fiber filters were combusted in crucibles in a muffle furnace at 550 °C for at least 10 h to determine percent of inorganic and organic solids (U.S. Environmental Protection Agency 1993). We conducted simple linear regression in Matlab R2014a, to calculate the slope of the relationship, as well as the coefficient of determination for the fit of the relationship between percent organic matter and suspended-sediment concentration, as well as between percent organic matter and bulk density in newly accreted material. Additional summary statistics and graphs were calculated and

created in Matlab R2014a. In R, an analysis of variance was used to determine if the differences in slopes of bulk density/organic matter relationships were statistically significant at the site level. Because of small sample sizes and non-normal data distributions, we used non-parametric tests (Wilcoxon rank sum test and two-sample Kolmogorov-Smirnov tests) in R to compare statistical differences between parameters with $\alpha = 0.05$. Choice of non-parametric test was dependent on whether variances were equal; this was also determined in R.

Results

Elevations

Mean elevations were greater at Mugu Lagoon compared with Seal Beach Wetlands. Mean elevation among all plots ($n = 34$) was 1.77 ± 0.03 m (mean \pm SE, range 1.54–2.07 m) at Mugu Lagoon. While mean elevation was 1.81 ± 0.03 m (mean \pm SE, $n = 25$) among random plots, mean elevation was 1.67 ± 0.01 m (mean \pm SE, $n = 9$) among transect plots. At Seal Beach Wetlands, mean elevation among all plots ($n = 33$) was 1.38 ± 0.04 m (mean \pm SE, range 0.56–1.68 m) at Seal Beach Wetlands. While mean elevation was 1.33 ± 0.06 m (mean \pm SE) among random plots ($n = 24$), mean elevation was 1.51 ± 0.02 m (mean \pm SE) among transect plots ($n = 9$). There was one random plot for which LiDAR data which was not available, but overall mean LiDAR-derived elevations were higher across the board. Furthermore, mean elevation across all feldspar plots at Mugu was 0.38 m above MHW, while mean elevation across all feldspar plots at Seal Beach was -0.73 m below MHW.

Precipitation and Runoff Data

In both individual rainfall events, more rain fell at Mugu Lagoon than Seal Beach Wetlands. Seal Beach Wetlands had 190 mm of precipitation for the entire study period, while Mugu Lagoon had 240 mm (Fig. 2). Dry weather dominated for most of the time, with no precipitation falling for 87% of the days during the study period at Mugu Lagoon and 91% of the days at Seal Beach Wetlands. Instantaneous discharge at Calleguas Creek peaked at $82 \text{ m}^3/\text{s}$ on 28 February 2014 after 48 mm of rain fell in a 24-h period at Mugu Lagoon, compared with 24 mm of rain at Seal Beach Wetlands (Fig. 3). Calleguas Creek discharge peaked at $170 \text{ m}^3/\text{s}$ on 12 December 2014 when 40 mm of rain fell in a 24-h period.

Vertical Accretion

Mugu Lagoon

Accretion and sediment parameters were low. Across the random plots, mean vertical accretion was 2 ± 0.3 mm/year (mean \pm SE,

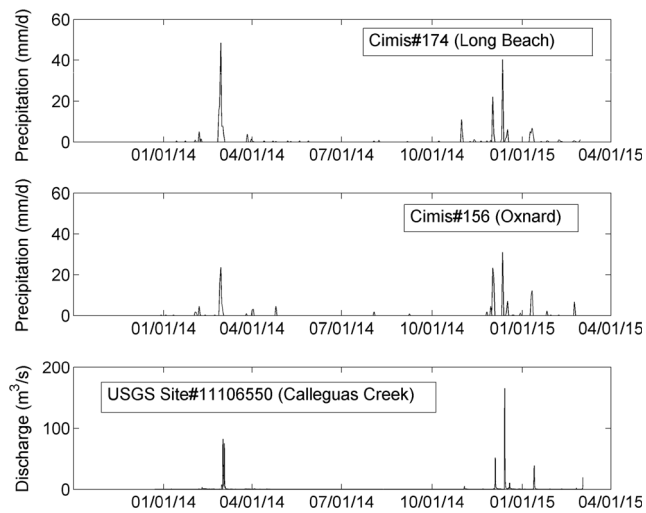


Fig. 2 Daily average precipitation (mm) totals for Seal Beach Wetlands (top) and central basin of Mugu Lagoon (Mugu Lagoon; center). Bottom graph shows instantaneous discharge values (m³/s) measured every 5 min for Calleguas Creek. Daily measurements of precipitation for Seal Beach Wetlands were retrieved from the California Irrigation Management Information System (CIMIS) site no. 174 (<http://www.ipm.ucdavis.edu>), which is 7 km north of the site. Daily measurements of precipitation for Mugu Lagoon were retrieved from CIMIS site no. 156 (<http://www.ipm.ucdavis.edu>), located approximately 17 km northwest of the site. Calleguas Creek instantaneous creek discharge measurements (m³/s) were obtained from a stream gage upstream from Mugu Lagoon (<http://waterdata.usgs.gov/nwis>)

range 0–7 mm/year; Table 1). Mean bulk density was $0.58 \pm 0.15 \text{ g/cm}^3$ (mean \pm SE, range 0.24–0.92 g/cm³), and organic matter was $18 \pm 2.6\%$ (mean \pm SE, range 5–42%; Table 1).

Accretion decreased from the edge of tidal creeks inland. Mean accretion was $2 \pm 0.3 \text{ mm/year}$ at 3 m from the tidal creek edge (mean \pm SE, range 1–3 mm/year; Table 1),

$1 \pm 0.3 \text{ mm/year}$ at 10 m (mean \pm SE, range 0–2 mm/year; Table 1), and $1 \pm 0.4 \text{ mm/year}$ at 30 m (mean \pm SE, range 0–3 mm/year; Table 1). Mean bulk density was $0.68 \pm 0.079 \text{ g/cm}^3$ at 3 m from tidal creek edges (mean \pm SE, range 0.54–0.90 g/cm³; Table 1), $0.56 \pm 0.4 \text{ g/cm}^3$ at 10 m (mean \pm SE, range 0.46–0.61 g/cm³; Table 1), and $0.49 \pm 0.39 \text{ g/cm}^3$ at 30 m (mean \pm SE, range 0.46–0.54 g/cm³; Table 1). Mean percent organic matter was $15 \pm 1.4\%$ at 3 m from tidal creek edges (mean \pm SE, range 12–18%; Table 1), $19 \pm 5.6\%$ at 10 m (mean \pm SE, range 14–27%; Table 1), and $23 \pm 6.4\%$ at 30 m (mean \pm SE, range 22–26%; Table 1).

The mean accretion rate of the random plots was not statistically different from the mean accretion rate of creek edge to inland transects. Furthermore, mean percent organic matter and mean bulk density values of the random plots were not statistically different than the values at 10 m from the edge of the tidal creek ($p > 0.05$). Patterns of percent organic matter and bulk density were the inverse of each other, as mean percent organic matter increased by 8% from 3 to 30 m (although the difference was not significantly different) and mean bulk density decreased by 26% from 3 to 30 m, which was statistically significant ($W = 23.5, p < 0.05$).

Seal Beach Wetlands

Accretion and bulk density were high. Across the random plots, mean vertical accretion was $6 \pm 0.5 \text{ mm/year}$ (mean \pm SE, range 1–10 mm/year; Table 1). Mean bulk density was $0.67 \pm 0.15 \text{ g/cm}^3$ (mean \pm SE, range 0.22–0.94 g/cm³), and organic matter was $12 \pm 2\%$ (mean \pm SE, range 6–34% (Table 1).

Accretion and sediment parameters were similar to transects. Mean accretion was $6 \pm 0.7 \text{ mm/year}$ at 3 m from tidal creek edge

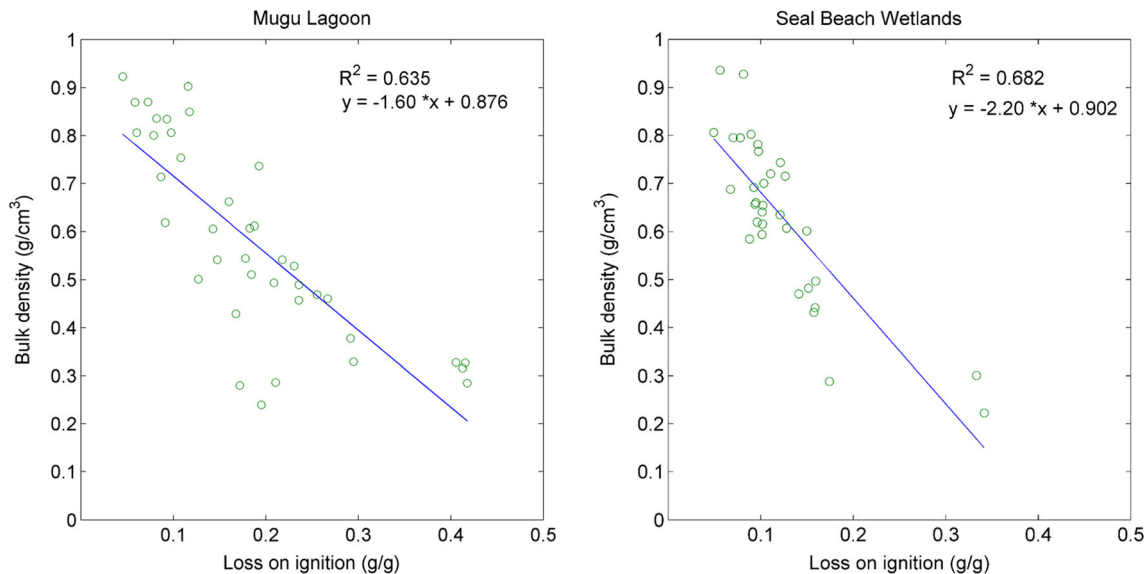


Fig. 3 The relationship of bulk density (BD) and loss on ignition (LOI) in the Seal Beach Wetlands National Wildlife Refuge (right) and the central basin of Mugu Lagoon (left)

Table 1 Accretion (mm/year), bulk density (BD; g/cm³), and percent organic matter (OM; mean ± SE), in surface samples at the central basin of Mugu Lagoon and Seal Beach Wetlands

Site (location)	<i>n</i>	Accretion (mm/year)	<i>n</i>	BD (g/cm ³)	<i>n</i>	OM (%)	Sediment flux (g/year)
Mugu Lagoon (random)	41	2 ± 0.3	27	0.58 ± 0.15	27	18 ± 2.6	290
Mugu Lagoon (3 m)	4	2 ± 0.3	4	0.68 ± 0.079	4	15 ± 1.4	340
Mugu Lagoon (10 m)	6	1 ± 0.3	4	0.56 ± 0.40	4	19 ± 5.6	140
Mugu Lagoon (30 m)	6	1 ± 0.4	4	0.50 ± 0.042	4	23 ± 1.6	125
Seal Beach (random)	20	6 ± 0.5	17	0.67 ± 0.15	17	12 ± 1.8	1005
Seal Beach (3 m)	6	6 ± 0.7	6	0.65 ± 0.051	6	10 ± 1.3	975
Seal Beach (10 m)	5	6 ± 1	5	0.61 ± 0.030	5	11 ± 1.7	915
Seal Beach (30 m)	6	6 ± 3	5	0.49 ± 0.29	5	17 ± 5.1	735

Marker horizons were poured between late December 2013 and early February 2014. Horizon markers were sampled in February 2015. We also calculated sediment flux (g/year) for a 0.25-m² plot

n = Sample size

(mean ± SE, range 4–9 mm/year; Table 1), 6 ± 1 mm/year at 10 m (mean ± SE, range 3–9 mm/year; Table 1), and 6 ± 3 mm/year at 30 m (mean ± SE, range 0–18 mm/year; Table 1). Mean bulk density was 0.65 ± 0.051 g/cm³ at 3 m from tidal creek edges (mean ± SE, range 0.47–0.81 g/cm³; Table 1), 0.61 ± 0.030 g/cm³ at 10 m (mean ± SE, range 0.50–0.69 g/cm³; Table 1), and 0.49 ± 0.29 g/cm³ at 30 m (mean ± SE, range 0.29–0.78 g/cm³; Table 1). Mean percent organic matter was 10 ± 1.3% at 3 m from tidal creek edges (mean ± SE, range 5–14%; Table 1), 11 ± 1.7% at 10 m (mean ± SE, range 7–16%; Table 1), and 17 ± 5.1% at 30 m (mean ± SE, range 10–33%; Table 1).

The mean accretion rate of the random plots was not statistically different from the mean accretion in all of the transect locations (*p* > 0.05). Patterns of percent organic matter and bulk density were the inverse of each other, as mean percent organic matter increased by 7% from 3 to 30 m and bulk density decreased by 25% from 3 to 30 m; although the difference in measured values was not statistically significant. Mean percent organic matter of the random plots was not significantly greater than the mean percent organic matter at 10 m from the edge of the tidal creek while mean bulk density in the random plots was not significantly greater than mean bulk density at 3 m from the edge of the tidal creek (*p* > 0.05).

Sediment Flux

An estimate of sediment fluxes show that Seal Beach Wetlands (1005 g/year) is accumulating more sediment than Mugu Lagoon (290 g/year) for equal areas of salt marsh. Seal Beach Wetlands accumulated similar amounts of sediment at 3 m (975 g/year) and 10 m (915 g/year) distances from the large tidal creek, while Mugu Lagoon accumulated lesser amounts at both 3 m (340 g/year) and 10 m (140 g/year). Sediment accumulation away at 30 m (290 g/year) from the large tidal creek at Seal Beach Wetlands was six times greater than sediment accumulation at 30 m from the smaller tidal creek at Mugu Lagoon.

Relationship of Bulk Density to Percent Organic Matter

A combined site regression analysis found an inverse relationship between LOI and bulk density (*r*² = 0.63, *n* = 72); however, the decline was 27% steeper at Seal Beach Wetlands (slope = -2.2) compared with Mugu Lagoon (slope = -1.6). These differences in slopes were statistically significant (*df* = 1, *SS* = 335, *F* = 12, *p* < 0.05). Also, the fit of slopes was similar at Mugu Lagoon (*r*² = 0.64, *n* = 39) and Seal Beach Wetlands (*r*² = 0.68, *n* = 33) (Fig. 3).

Suspended-Sediment Concentration

Mugu Lagoon

Dry-weather suspended-sediment concentrations were low and similar within and across sites. Across transects, dry-weather suspended-sediment concentrations during flood tide were 37 ± 1.8 mg/L (mean ± SE, range 7–88 mg/L, *n* = 120), while mean percent organic matter was 26 ± 2% (mean ± SE, range 0–100%, *n* = 120). Suspended-sediment concentrations were 51 ± 5 mg/L (mean ± SE, range 28–88 mg/L) at 0 m (*n* = 12), 40 ± 6 mg/L (mean ± SE, range 7–76 mg/L) at 10 m (*n* = 12), and 35 ± 5 mg/L (mean ± SE, range 11–59 mg/L) at 31 m (*n* = 12) from the creek edge (Fig. 4). Percent organic matter was 16 ± 2% (mean ± SE, range 0–25%) at 0 m (*n* = 12), 24 ± 4% (mean ± SE, range 0–50%) at 10 m (*n* = 12) and 25 ± 7.7% (mean ± SE, range 0–100%) at 31 m (*n* = 12) from the edge. Differences in suspended-sediment concentrations and percent organic matter in these monitoring stations were not statistically significant (*p* > 0.05).

Wet weather suspended-sediment concentrations were high. For example during flood tide values were 177 ± 15 mg/L (mean ± SE, range 31–649 mg/L, *n* = 109), while mean percent organic matter was 15 ± 1% (mean ± SE, range 0–33%, *n* = 109). Suspended-sediment concentration was 264 ± 61 mg/L

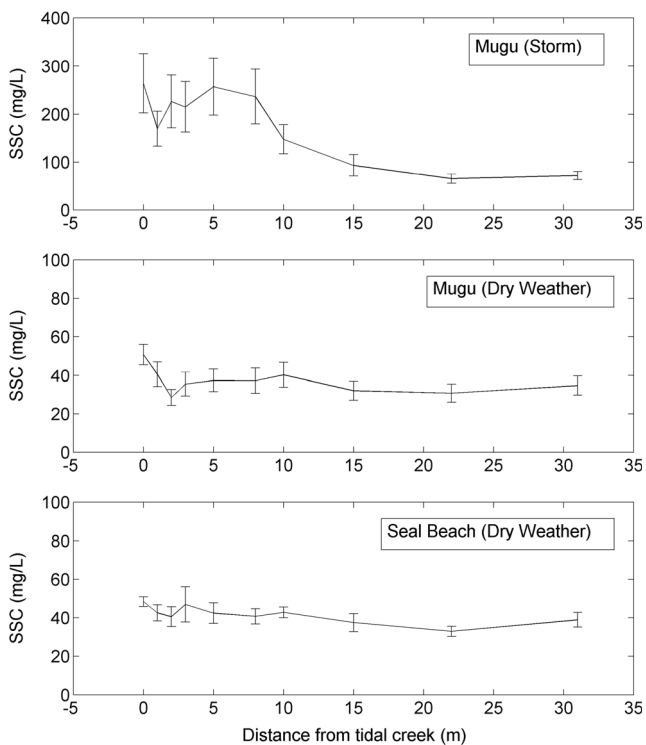


Fig. 4 The effect of distance to tidal creek on suspended-sediment concentrations (mg/L) in the central basin of Mugu Lagoon (Mugu Lagoon) during a storm (27 February to 2 March; *top*), in Mugu Lagoon during dry weather (*center*), and in Seal Beach Wetlands (*bottom*). Highest suspended-sediment concentrations were found within the first 10 m of the edge of tidal creeks. Error bars represent \pm SE ($n = 3$). Original data from Rosencranz et al. (2016)

(mean \pm SE, range 79–618 mg/L) at 0 m ($n = 12$), which was statistically different from the 31 m concentration ($D = 0.6667$, $p < 0.05$), but not the 10 m concentration. Suspended-sediment concentration was 148 ± 30 mg/L (mean \pm SE, range 38–312 mg/L) at 10 m ($n = 11$) and 72 ± 8 mg/L (mean \pm SE, range 38–115 mg/L) at 31 m ($n = 8$) from the edge (Fig. 5). Percent organic matter was $14 \pm 1\%$ (mean \pm SE, range 9–21%) at 0 m ($n = 12$), $14 \pm 2\%$ (mean \pm SE, range 0–27%) at 10 m ($n = 11$), and $17 \pm 1\%$ (mean \pm SE, range 13–24%) at 31 m ($n = 8$) from the edge, although differences were not statistically different from each other ($p > 0.05$).

Seal Beach Wetlands

Across transects, dry-weather suspended-sediment concentrations were 41 ± 2 mg/L (mean \pm SE, range 17–111 mg/L, $n = 90$), while mean percent organic matter was $15 \pm 1\%$ (mean \pm SE, range 0–43%, $n = 90$). Suspended-sediment concentration was 48 ± 2 mg/L (mean \pm SE, range 37–61 mg/L) at 0 m ($n = 9$), 43 ± 3 mg/L (mean \pm SE, range 32–59 mg/L) at 10 m ($n = 9$), and 39 ± 4 mg/L (mean \pm SE, range 24–64 mg/L) at 31 m ($n = 9$) from the creek edge (Fig. 4). Organic matter percent was $18 \pm 2\%$ (mean \pm SE, range 13–27%) at 0 m ($n = 9$), $16 \pm 3\%$ (mean \pm SE, range 7–

27%) at 10 m ($n = 9$), and $15 \pm 3\%$ (mean \pm SE) at 31 m ($n = 9$) from the edge.

While suspended-sediment concentrations at 0 m were significantly greater than concentrations at 10 m and 31 m ($D = 0.6296$, $p < 0.05$), differences in suspended-sediment concentrations at 10 m and 31 m were not significantly different ($p > 0.05$). Furthermore, differences in measured values of percent organic matter were not statistically significant.

Relationship of Organic Matter to Suspended-Sediment Concentration

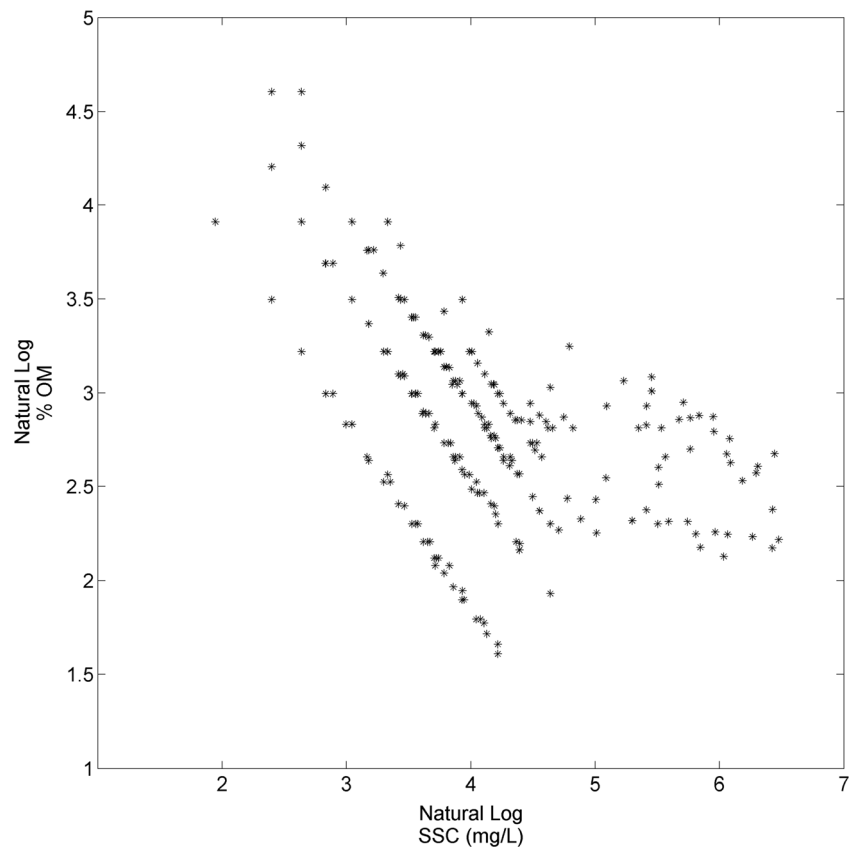
Across all sites, at dry-weather suspended-sediment concentrations less than approximately 110 mg/L, there was an inverse relationship between suspended-sediment concentrations and percent organic matter (Fig. 5). All suspended concentrations above 110 mg/L were observed at Mugu Lagoon during wet weather, where the pattern of decline in percent organic matter was less steep compared with dry-weather periods. When suspended concentrations were above 110 mg/L, mean percent organic matter was stable and remained below 33%.

Discussion

Our objectives were to determine: (1) short-term salt marsh surface accretion rates for these two common types of southern California salt marshes; (2) the spatial patterns of accretion and suspended-sediment concentrations; and (3) the impact of wet and dry weather, during a drought period, on sedimentation patterns. We found that short-term marsh-wide accretion rates were 77% lower in a higher elevation, less-modified, pickleweed-dominated marsh (Mugu Lagoon) compared with a lower elevation, highly modified marsh with extensive cordgrass (Seal Beach Wetlands). Spatial patterns of dry-weather suspended-sediment patterns and magnitudes from the tidal creek edge to the interior were similar between the marshes; while spatial patterns of accretion were different (e.g., accretion did not decline from the edge of the tidal creek to the interior at Seal Beach Wetlands). At Mugu Lagoon, spatial patterns and magnitudes of suspended sediment changed (i.e., greater near edge of tidal creek) during peak runoff following a storm.

Suspended-sediment concentrations coupled with tide range can be used to predict the limits to sea-level rise that a salt marsh can survive (Kirwan et al. 2016). Assuming tide range is static, and the spatial and temporal patterns of suspended-sediment concentrations do not change, dry-weather suspended-sediment concentrations alone suggest that both salt marshes could keep pace with a sea-level rise rate of approximately 3 m/100 year, a rate that is 43% greater than high SLR scenarios (1.7 m/100 year) for this region (National Resource Council 2012). However, our coupled suspended sediment and accretion measurements at

Fig. 5 The relationship of natural log of suspended-sediment concentration (*SSC*) to natural log of percent organic matter for the central basin of Mugu Lagoon (Mugu Lagoon) during a storm (27 February to 2 March), at Mugu Lagoon during dry weather, and at Seal Beach Wetlands National Wetlands during dry weather. Original data from Rosencranz et al. (2016)



Mugu Lagoon suggest that the pattern of accretion is set by infrequent large flooding, which agrees with past findings at the site. Extreme flood events with extensive overflow from Calleguas Creek in previous years have resulted in visible sediment deposition on marsh surfaces (Onuf 1987). The accretion rates observed at Seal Beach Wetlands are low compared with measured *Spartina*-dominated marsh accretion rates in Tijuana Estuary between 1992 and 1994, which ranged between 14 and 60 mm/year (Cahoon et al. 1996). However, the salt marsh accretion rates at Mugu Lagoon are slightly higher compared with the range of those observed in the *Salicornia*-dominated salt marsh from the same study (0.7–1.4 mm/year). The decline, from tidal creek to interior, although not statistically significant, was most apparent in creek edge to inland transects, which measured accretion and storm-related suspended sediments in Mugu Lagoon. This pattern suggests that the mineral sediment that is being delivered to the marsh is contributing to accretion along the creek edge at a higher rate than farther away from the creek.

While accretion at Seal Beach may be higher simply due to the fact that Seal Beach is lower in the tide frame, there could be an effect of channel area and density that warrants further investigation. In Seal Beach Wetlands, the decay from edge to interior was less apparent where samples were taken parallel to a creek that was an order of magnitude wider than the creek sampled at Mugu Lagoon. Furthermore, the backside of one

transect at Seal Beach Wetlands approached a creek of similar width to that of Mugu Lagoon's main channel. Therefore, the larger channel area and increased channel density might be contributing to the high accretion rate at Seal Beach.

In the systems studied here, tidal creeks appear to play an important role in delivering turbid waters to the salt marsh plain via a watershed sediment source during runoff events; although, elevation and marsh age (Chen et al. 2016) may also drive the surface processes we observed. Although we did not measure elevation at individual plots at Seal Beach Wetlands, bulk density may have been higher in the random plots (Table 1) because transects were located in higher elevations (Fig. 1). Across marsh, differences in bulk density (higher at Seal Beach Wetlands) and organic matter (higher at Mugu Lagoon) may also be related to geomorphic and plant community differences. In the San Francisco Bay Area salt marshes, Callaway et al. (2012) found that mineral accumulation rates were higher at low-marsh stations within individual sites. In our study, distance to tidal creek appears to influence bulk density and organic matter patterns in recently accreted sediments.

Our results support the notion that point measurements of accretion rates and suspended concentrations alone can be a misleading indicator of salt marsh stability (Kirwan et al. 2008). Although the recent subsidence history for the salt marsh at Mugu Lagoon is unknown, Seal Beach Wetlands has been

subsiding between 2 and 8 mm/year since 1968. Subsidence at Seal Beach Wetlands is due to a combined effect of groundwater, oil, and gas extraction (Takekawa et al. 2014), which increases inundation frequency and would potentially lead to higher accretion rates in order for the marsh plain to maintain an equilibrium with sea level (Morris et al. 2002). Furthermore, if the pattern of accretion is set by infrequent flooding events, then differences in dry-weather suspended-sediment concentrations may not predict salt marsh resilience to sea-level rise.

A better spatial and temporal understanding of sources and mechanisms of sedimentation in highly modified marshes is needed to assess the vulnerability of these salt marshes to sea-level rise. For example, Ganju et al. (2015) suggest using the differential between flood and ebb tide SSC as an indicator of salt marsh stability. In a mid-Atlantic salt marsh, an unstable salt marsh was characterized by a -18 -mg/L flood-ebb differential. In Seal Beach Wetlands and Mugu Lagoon, Rosencranz et al. (2016) observed the differentials of mean flood and ebb SSC to be approximately zero in two channels at Seal Beach Wetlands and Mugu Lagoon. Conversely, another channel at Seal Beach Wetlands had a flood-ebb differential that was -2 mg/L. Given the balanced fluxes that have been observed in the system, relative to the large exports from the Mid-Atlantic salt marsh, we assume that the flood-ebb differentials are similar on the salt marsh plain in our study sites. However, suspended-sediment samples during ebb tide are needed to confirm this.

Salt marsh resilience models, such as SLAMM and the Wetland Accretion Rate Model of Ecosystem Resilience (WARMER) (Swanson et al. 2013) apply a regional accretion rate to many sites (Zhang and Gorelick 2014) or accretion rates specific to marsh zone within a single site (Swanson et al. 2013). We found accretion rates were higher near creeks and at lower elevation sites on the marsh plain, although these relationships were not statistically significant. These patterns are being influenced by sediment delivery via large storm events. These results can be incorporated into spatially explicit sea-level rise modeling efforts to help build a better understanding of salt marsh resilience to sea-level rise.

Conclusions

This study enumerated patterns of accretion and suspended-sediment dynamics in two representative southern California salt marshes of a Mediterranean climate. While both marshes appear to be keeping pace with current rates of sea-level rise (National Resource Council 2012), the magnitude and patterns of mineral sediment concentration and accretion, along with no known recent elevation decreases at Mugu Lagoon (Rosencranz et al. 2016), suggest it may be the more resilient marsh under the low sea-level rise scenario (4 mm/year)—an

optimistic projection for the region (Kopp et al. 2014). Despite high accretion rates, salt marshes at Seal Beach Wetlands, which are low in the tide frame, and may receive some sediment from Anaheim Bay, are experiencing short-term decreases in surface elevations (Rosencranz et al. 2016), and are not likely to keep pace with sea-level rise in the absence of large inputs from storms or sediment augmentation. Terrigenous storm deposits are typically the only source of large increases in cordgrass accretion rates in mid-Atlantic, USA (Stumpf 1983) and southern California (Cahoon et al. 1996) salt marshes. Past wet-weather storm deposits from wetter years (e.g., Onuf 1987) suggest Mugu Lagoon, which has a watershed sediment source, has the potential to adjust to higher rates of sea level. On the other hand, Seal Beach Wetlands, which has a watershed sediment source consisting of flood control channels, would need similar magnitudes of sediment during wet periods to keep pace and the potential of such supply remains uncertain based on our available data. In both marshes, observations of higher inorganic concentrations near the edge of tidal creeks confirm that tidal creeks are the main source of mineral sediment through resuspension and/or watershed sediment transport; although our study did not assess all potential sources of sediment at both sites. Current accretion rates may not match future rates, particularly with extended droughts predicted into the future (MacDonald et al. 2016), but our study provides an important and current snapshot of the spatial and temporal variability in salt marsh surface sediment processes. The ability of a marsh to accrete via in situ organic matter production is inherently limited, so it makes understanding the spatial and temporal patterns of sediment deposition paramount to assessing vulnerability (Morris et al. 2016). Although this study only addressed inorganic sedimentation, it is recognized that organics also play a role in net accretion. At this time, there is not enough known to estimate the proportion of this second-sediment source in net accretion in our systems. Based on the results of this study, we predict that Mugu Lagoon's accretion rate is likely to increase as sea-level rises, while Seal Beach Wetlands's accretion rate is likely at, or close to, its upper limit based on the low availability of mineral sediment due to a lack of watershed sediment source.

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Appendix. Map of flood control channels in the Catchment of Seal Beach Wetlands

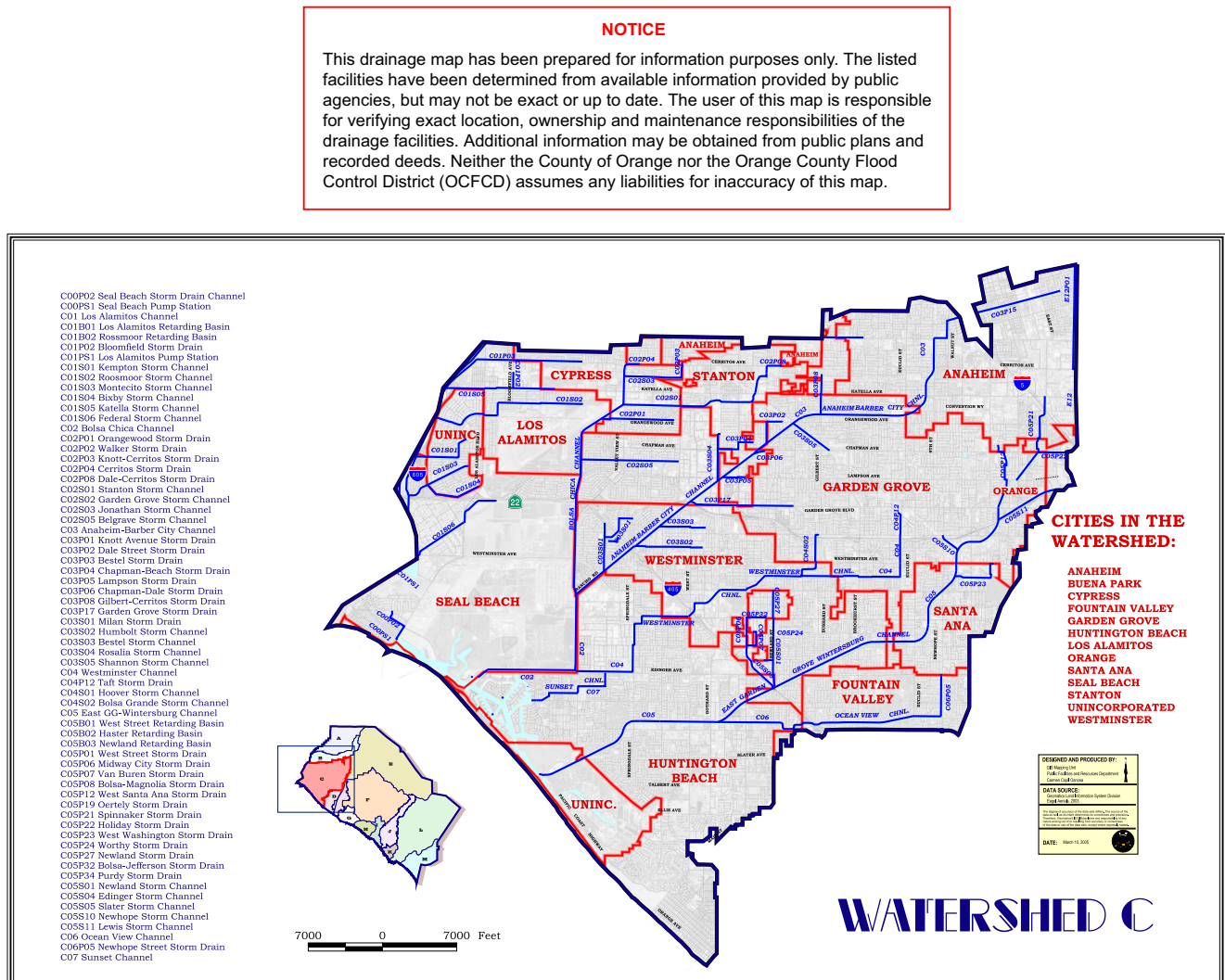


Fig. 6 Watershed map showing different flood control channels that may provide sediment to Seal Beach Wetlands (source: <http://www.ocflood.com/civicax/filebank/blobdload.aspx?blobid=32723>)

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