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1The role of sediment dynamics for inorganic accretion patterns in southern
2California'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/yr (mean $\pm$ SE) and 2 ± 0.3 mm/yr. Also, the estimated sediment flux (g/yr) 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 to Mugu Lagoon.

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

38Introduction

39 Salt marshes provide a myriad of ecosystem services, such as trapping pollutants,
40storing carbon, and providing critical breeding habitat for endangered birds (Massey et al.
411984; Powell 1993; Costanza et al. 1997; Chmura et al. 2003; Barbier et al. 2010).
42Despite their intrinsic and utilitarian values, these resources are threatened by past and
43current habitat conversion, climatic factors, and future rates of relative sea-level rise
44(Kirwan et al. 2010; National Resource Council 2012; Kirwan & Megonigal 2013).
45Global sea-level rise could cause salt marshes to migrate landward, and/or could lead to
46shifts in habitat types. Some salt marshes with high accretion potential will persist under
47high rates of sea-level rise (Kirwan et al. 2016), but because local processes are variable
48between sites, local site data is needed to predict resilience (Webb et al. 2013).
49Understanding and mitigating the impacts of sea level rise is difficult because fine scale
50elevation changes may cause drastic shifts in inundation patterns, sedimentation and plant
51abundance, distribution, and productivity across marshes (Kirwan & Guntenspergen
522012; Janousek et al. 2016). If salt marshes cannot keep pace with sea-level rise the
53availability of transgression habitat will play a key role in the future persistence of these
54habitats (Schile et al. 2014), but in the highly urbanized region of southern California,
55transgression habitat is limited. In anticipation of sea-level rise effects, and assuming
56transgression habitat will continue to be limited, vulnerability assessments can inform
57management actions within the current extent of salt marsh. These assessments include
58shoreline stabilization, marsh drainage restoration, and elevation augmentation, which
59can mitigate future salt marsh collapse (Wigand et al. 2015).

60 Current tide range and sediment supply affect a salt marsh's ability to keep pace
61 with sea-level rise (Raposa et al. 2016). Mineral deposition in marshes is often an
62 episodic process, with strong linkages to storm magnitude and frequency (Reed 1989;
63 Cahoon et al. 1996; Turner et al. 2006). Southern California coastal marshes differ from
64 marshes in many other parts of the world due to the highly seasonal winter precipitation
65 regime of the Mediterranean climate. Almost all precipitation and storm events occur in
66 the winter months and often are delivered in a few, larger storm events during
67 atmospheric rivers or strong El Niño years (Warrick & Farnsworth 2009; Dettinger 2013).
68 Future climate change predictions in the southwest United States suggest that the region
69 may experience more frequent and intense droughts (MacDonald 2010; MacDonald et al.
70 2016). Therefore, we need to understand vertical accretion and associated sediment
71 dynamics in salt marsh ecosystems during extended periods of dry weather, as well as
72 during storms, in order to inform future management actions for salt marshes.

73 These events may have different impacts on sedimentation and accretion
74 depending on tidal elevation. For example, Cahoon et al. (1996) observed that low marsh
75 zones were accreting more than high marsh zones during storm-driven stream flows in a
76 salt marsh in the Tijuana Estuary. Other studies have found that high rates of accretion in
77 natural and restored portions of Tijuana estuary salt marshes are mainly due to sediment
78 deposition from storms (Weis et al. 2001; Callaway & Zedler 2004; Wallace et al. 2005).
79 Similarly, Mugu Lagoon has experienced loss of open water habitat due to large sediment
80 deposition during El Niño events (Onuf 1987). However, some Mediterranean-climate
81 salt marshes in other regions, such as Venice Lagoon, Italy (Day et al. 1998), San
82 Francisco Bay Area, California (Callaway et al. 2012), and Ebro Delta, Spain (Calvo-

83Cubero et al. 2013), have been highly modified due to agriculture and urban uses, and
84consequently have highly variable sedimentation rates. Watershed-level comparisons in
85non-Mediterranean climate zone marshes show that watershed sediment availability is a
86key component of future resilience to accelerated sea level rise (Day et al. 2011).

87 Within the marshes, vegetation structure can also play a role in altering flows and
88consequently trapping sediment and reducing erosion on the marsh plain (Boorman et al.
891998). Results like these are useful for understanding intra-marsh elevation differences in
90the face of sea level rise; however, a better understanding of inter-marsh differences is
91useful for comparing watershed level effects, and ultimately management of isolated tidal
92salt marshes, which are common in the topographically isolated Pacific Coast. Large-
93scale models such as Sea Level Affecting Marshes Model (SLAMM) have predicted
94catastrophic effects on a variety of salt marshes because they apply static, regional
95parameters to individual sites that are shaped by different processes (Kirwan et al. 2016).
96Site specific differences are apparent in southern California, where recent short-term
97comparisons of surface elevation change between Seal Beach Wetlands (449 days), and
98Mugu Lagoon (664 days) show that the low salt marsh at Seal Beach Wetlands (-1.2
99mm/year) is losing elevation faster than the low salt marsh at Mugu Lagoon (1.6 mm/yr)
100(Rosencranz et al. 2016).

101 Conceptually, these elevational patterns are determined by the elevation of the salt
102marsh plain, tidal range, subsurface organic accretion, erosion, as well as surface
103accretion and suspended sediment concentration (Morris et al. 2002; Wallace et al. 2005;
104Swanson et al. 2013). Within salt marshes, these patterns are spatially variable. Previous
105research in marshes of different climates and different vegetation zones has indicated a

106decline in sediment deposition from the tidal creek edge to the interior (Reed et al. 1999;
107Christiansen et al. 2000; Moskalski & Sommerfield 2012). Here we address the
108question of how much spatial variability in inorganic sediment deposition related to
109surface morphology and channels is apparent in two southern California salt
110marshes. Specifically, we ask 1) how critical are wet and dry weather periods in the
111timing and magnitude of accretion, and 2) how do surface morphology and channels
112impact the spatial variability of mineral sedimentation and overall salt marsh
113evolution? Answering these questions can aid in assessing the vulnerability of salt
114marshes to future sea-level rise and extreme events.

115 Salt marsh zonation patterns of southern California are unique compared to other
116North American salt marshes because they are dominated by pickleweed, and may only
117have cordgrass in low elevations and/or along tidal creek edges. Spatial zonation patterns
118are due to the effects of inundation patterns (Zedler 1982; Zedler et al. 1999). While
119cordgrass occurs in lower elevations, pickleweed and other shrubby halophytes like salt
120grass (*Distichlis spicata*) occur in the higher elevations of the salt marsh zones (Zedler et
121al. 1986). Episodic and infrequent storm events may induce rapid habitat conversion of
122pickleweed to cordgrass by increasing the frequency and depth of inundation (Zedler
1231983). Conversely, rapid sedimentation can increase elevations, facilitating cordgrass
124colonization of exposed mudflat and pickleweed domination of dessicating cordgrass
125patches (Ward et al. 2003). Thus, fine scale sediment deposition patterns play an
126important role in the characteristic zonation of southern California salt marshes, as well
127as 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 & Zedler 2008) compared to 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° 40'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 hectares 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 (Thorne et al. 2016). Predicted maximum

150 tide range was 2.6 m for 2013 (Mugu Lagoon Ocean Pier;
151 http://tidesandcurrents.noaa.gov/tide_predictions.html). The site is one of the least
152 impacted regions of the lagoon and lies along a dendritic tidal creek approximately 1.1
153 kilometers in length (Fig. 1). Tidal creeks are typically bordered by pickleweed and
154 fleshy jaumea (*Jaumea carnosa*) in the lower elevations and salt grass in the higher
155 elevations. There is also an undeveloped upland transition zone, which is rare for the
156 southern California region because of high-density coastal urbanization.

157 Mugu Lagoon lies at the base of the Calleguas Creek watershed, which has been
158 altered significantly due to human activities (Sheng & Wilson 2009; Beller et al. 2011).
159 Historically, Calleguas Creek was only connected to Mugu Lagoon via shallow sloughs
160 and sheet flows during heavy rains. Today, the creek drains a 64231 hectare watershed -
161 measured at USGS stream gage located 9 km upstream from Mugu Lagoon (Hydrologic
162 Unit Code 18070103; <http://waterdata.usgs.gov/nwis>). The creek is characterized by
163 perennial low freshwater flows and low concentrations of sediment in Calleguas Creek
164 during dry weather due to agricultural irrigation, urban runoff and discharge from an
165 upstream wastewater treatment plant. Large winter storms can greatly increase discharge
166 and suspended sediment concentrations (Onuf 1987).

167 *Seal Beach Wetlands*

168 Also located within a navy base (Naval Weapons Station Seal Beach) and of
169 similar size to Mugu Lagoon, the Seal Beach Wetlands (Seal Beach Wetlands) (34° 44'N,
170 118° 05'W) encompass approximately 390 ha of salt marsh (Fig. 1). Our study focused on
171 an approximately 206 hectares, excluding major tidal creeks and mudflats. Mean High
172 Water (MHW) is 2.06 m measured at Station 9410680 Long Beach Terminal Island, CA

173(<http://tidesandcurrents.noaa.gov/>). Predicted maximum tide range at this tide gage in
1742013 was 2.7m. In Seal Beach Wetlands, tidal creeks are typically bordered by cordgrass.
175In contrast to Mugu Lagoon, where upland transition zone is present and the marsh
176remains connected to a terrestrial watershed, Seal Beach Wetlands is surrounded by
177extensive suburban development beyond the boundaries of the Naval Station and has no
178direct link to a terrestrial sediment source (e.g. creek or river). Within the Naval Station
179there are adjacent agricultural and upland ecosystems.

180 Historically, Seal Beach Wetlands existed in one of the largest contiguous valley
181plain watersheds in southern California, receiving episodic storm flows and sediment
182from the meandering Santa Ana and the San Gabriel Rivers (Grossinger et al. 2011)
183{Grossinger, 2011, Historical wetlands of the southern California coast: An atlas of US
184coast survey t-sheets`, 1851-1889}. Both rivers existed as braided channels and shifted
185paths during major flooding events. In response to flood damage between late 19th and
186early 20th centuries, the Santa Ana and San Gabriel rivers were channelized for flood
187control purposes, and today Seal Beach Wetlands exists in one of the most extensively
188urbanized basins in southern California (Brownlie & Taylor 1981; Stein et al. 2007). Five
189flood control channels – Bolsa Chica, Anaheim-Barber City, Westminster, East Garden
190Grove Wintersburg, and Ocean View Channel – drain 23237 hectares of urban landscapes
191into Anaheim Bay, but not directly into Seal Beach Wetlands (Appendix 1: Map of flood
192control channels in the Catchment of Seal Beach Wetlands.). Flood control channels like
193these may result in reduced terrigenous sediment to estuaries. Specifically, 73% of
194sediment reductions have occurred in urban rivers (e.g., watersheds of Seal Beach), with

195only a 20% reduction of sediment in the Transverse Range (e.g., watershed of Mugu
196Lagoon) (Warrick & Farnsworth 2009).

197*Estimates of Salt Marsh Elevation*

198 Digital elevation models were used to estimate relative differences in elevation
199between marsh sites [DEM; 2009-2011 California Coastal Conservancy LiDAR Project:
200<https://data.noaa.gov/dataset/2009-2011-ca-coastal-conservancy-coastal-lidar-project>;
201vertical datum: North American Vertical Datum of 1988 (NADV88)]. These data were
202uncorrected for vegetation interference. All of our sampling locations were overlaid on
203the DEM in ArcMap 10.2.1, and elevations were obtained using the point extract values
204to points tool. Elevation statistics were calculated using pivot tables in Microsoft Excel.

205*Vertical accretion*

206 To assess within- and between-marsh accretion variability, 50 feldspar marker
207horizons (Cahoon & Turner 1989) were poured in vegetated areas in each wetland at
208Mugu Lagoon and Seal Beach Wetlands from 21 December 2013 to 2 January 2014 (Fig.
2091). Plot locations were determined using a random point generator (geomidpoint.com)
210within sections of a 5 x 5 m grid overlay on an aerial image of each wetland
211(earth.google.com).

212 In order to capture spatial variability within the salt marshes, as well as
213sedimentation patterns from storm and over marsh sediment deposition, we re-sampled
214three replicate transects of feldspar at 3 m, 10 m and 30 m from the edge of tidal creeks at
215Mugu Lagoon and Seal Beach Wetlands (Fig. 1); plots that had been established and
216sampled once in a previous study by Rosencranz et al. (2015). Transect plot locations

217were poured within the same timeframe as the randomly selected marker plots. Locations
218were determined in the field, with transects at least 50 m apart. Each plot was treated as
219an independent sample.

220 To establish the feldspar plots, we sprinkled 1200-1600 mL of dry Custer Feldspar
221clay within the perimeter of a 0.5 m by 0.5 m quadrat, shaking the vegetation thoroughly
222to settle the feldspar. Corners of the plots were marked with gray PVC pipe. Because we
223expected some plots to be lost due to erosion and bioturbation (Cahoon & Turner 1989),
224each sampling location had two adjacent, independent 0.5 m by 0.5 m plots (Fig. 1).

225 We sampled marker plots using a plug extraction method suitable for drier soils
226(Cahoon et al. 1996). The sampling method consisted of visually surveying the adjacent
227plots at each sampling location to see if any feldspar was exposed. If feldspar was visible
228in any area of the plot, we recorded accretion as zero. If the plot was covered by sediment
229(i.e. no feldspar was visible), we carefully extracted an approximately 3 x 3 x 6 cm plug
230with a serrated kitchen knife, measuring the newly formed sediment layer on each side of
231plug with a ruler or calipers to the nearest millimeter. Annual accretion rates (AR; mm/yr)
232were calculated using the following equation, where AM is measured accretion and L is
233age of plot in days:

234

$$235 \quad AR = AM / \left(\frac{L * 1 \text{ yr}}{365 \text{ d}} \right) \quad (1)$$

236

237Standard error (SE) for mean accretion rates was also calculated. If more than 1 mm
238accretion had occurred on the top of the plug, approximately 1 cm³ of recently accreted
239material was separated carefully from sediment layer above the feldspar, to avoid causing

240additional compaction; and the estimated 1 cm³ sediment volume was measured precisely
241using a syringe tube for further analysis. For bulk density, the 1 cm³ sample was dried at
242105 °C for 24 hrs in a drying oven, while percent organic matter (OM) was determined by
243combusting the dried sample for 4 hrs at 550°C in a furnace (Heiri et al. 2001). We
244recovered and sampled 41 of the 50 random horizon markers at Mugu Lagoon on 13 and
24515 February 2015. In one plot, feldspar was not observed, while eight additional plots
246were not recovered (i.e., plot stakes may have been lost or removed). Of the 41 random
247locations where sufficient accretion was observed, 27 independent surface samples were
248collected and analyzed in the laboratory. Also at Mugu Lagoon, we recovered and
249sampled eight of the nine transect horizon markers on 13 February 2015. Both plots at
250one location at 3 m from the tidal creek edge had disappeared and were likely eroded
251away, were disturbed by bioturbation, or were too deep to recover with the plug method;
252therefore at 3 m, 10 m, and 30 m sample sizes were unequal (n=4, n=6, and n=6,
253respectively). Of the 16 plot locations where accretion was observed in transects, 12
254surface samples were collected and analyzed in the laboratory. Due to low accretion, we
255were unable to collect surface samples from one of the three transects. In those cases, no
256calculations of bulk density or percent organic matter were made.

257 At Seal Beach Wetlands, we recovered and sampled 20 of the 50 random horizon
258markers on 14 and 27 February 2015. Of the 20 random locations where accretion was
259observed, 17 surface samples were collected and analyzed in the laboratory. Also at Seal
260Beach Wetlands, we recovered and sampled all of the nine transect horizon markers on 27
261February 2015.

Based on mean bulk density (BD;g/cm³) and mean accretion rates (AR;mm/yr), we could estimate sediment fluxes (Q; g/yr) 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.

275Meteorological and runoff data

Daily measurements of precipitation for Seal Beach Wetlands were retrieved from the California Irrigation Management Information System (CIMIS) site #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 #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>).

284 *Suspended Sediment Concentration*

285 Sediment delivery by tidal creeks was examined by collecting suspended
286 sediment samples using a modified single-stage water sampler (Inter-Agency Committee
287 on Water Resources Subcommittee On Sedimentation 1961) at 0, 1, 2, 3, 5, 8, 10, 15, 22,
288 31 m perpendicular to the edge of the major tidal creeks; suspended sediment
289 concentration sampling methods and data were originally published in Rosencranz et al.
290 (2015). Sample bottles were 0.25 L and were deployed during flood tides from January to
291 March 2014 along three replicate transects at Mugu Lagoon and Seal Beach Wetlands
292 (Fig. 1) parallel to the feldspar transects. At Mugu Lagoon, we sampled dry weather
293 suspended sediment concentrations on 28-31 January 2014 on four consecutive flood
294 tides, which occurred after a prolonged dry weather period. Because of different tide
295 heights and weather conditions during each day, each sample was treated as independent.
296 Also at Mugu Lagoon, on 28 February-3 March 2014, we sampled suspended sediment
297 concentrations on four flood tides, which occurred during a wet weather period, which
298 included any rain. At Seal Beach Wetlands, we sampled dry weather suspended sediment
299 concentrations between 1 January 2014 and 3 February 2014, on 10 consecutive flood
300 tides, all of which occurred after a prolonged dry weather period. No wet weather
301 suspended sediment concentrations were sampled at Seal Beach Wetlands. Since not all
302 samplers filled during each sampling period, which decreased sample sizes for some
303 interior sampling locations, we omitted data from all except three sampling events. In the
304 sampling events we retained for this study, all samplers filled during each sampling
305 event.

306 During a sampling event, samplers filled rapidly and represent an instantaneous
307suspended sediment value. Lab methods followed U.S. Environmental Protection Agency
308(1971) protocols. Blank glass fiber filters were washed with distilled water and dried for
309one hour at 103-105°C, then cooled in a desiccator. The entire sample was passed through
310the clean pre-weighed filter using a vacuum hose filtration set-up. Samples were dried at
311103-105°C for one hour, cooled in a desiccator and weighed to the nearest milligram.
312Samples were dried at 103-105°C for another 20-30 minutes, cooled in a desiccator, and
313re-weighed to confirm that no additional mass loss had occurred. Glass fiber filters were
314combusted in crucibles in a muffle furnace at 550°C for at least 10 hours to determine
315percent of inorganic and organic solids (U.S. Environmental Protection Agency 1993).
316We conducted simple linear regression in Matlab R2014a, to calculate the slope of the
317relationship, as well as the coefficient of determination for the fit of the relationship
318between percent organic matter and suspended sediment concentration, as well as
319between percent organic matter and bulk density in newly accreted material. Additional
320summary statistics and graphs were calculated and created in Matlab R2014a. In R, an
321analysis of variance was used to determine if the differences in slopes of bulk
322density/organic matter relationships were statistically significant at the site level. Because
323of small sample sizes and non-normal data distributions, we used non-parametric tests
324(Wilcoxon rank sum test and two-sample Kolmogorov-Smirnov tests) in R to compare
325statistical differences between parameters with $\alpha=0.05$. Choice of non-parametric test
326was dependent on whether variances were equal; this was also determined in R.

327**Results**

328***Elevations***

329 Mean elevations were greater at Mugu Lagoon compared to Seal Beach Wetlands.
330 Mean elevation among all plots (n=34) was 1.77 ± 0.03 m (mean $\pm$ SE, range 1.54-2.07
331 m) at Mugu Lagoon. While mean elevation was 1.81 ± 0.03 m (mean $\pm$ SE, n=25) among
332 random plots, mean elevation was 1.67 ± 0.01 m (mean $\pm$ SE, n=9) among transect plots.
333 At Seal Beach Wetlands, mean elevation among all plots (n=33) was 1.38 ± 0.04 m
334 (mean $\pm$ SE, range 0.56-1.68 m) at Seal Beach Wetlands. While mean elevation was 1.33
335 ± 0.06 m (mean $\pm$ SE) among random plots (n=24), mean elevation was 1.51 ± 0.02 m
336 (mean $\pm$ SE) among transect plots (n=9). There was one random plot for which LiDAR
337 data was not available, but overall mean LiDAR derived elevations were higher across
338 the board. Furthermore mean elevation across all feldspar plots at Mugu was 0.38 m
339 above MHW, while mean elevation across all feldspar plots at Seal Beach was -0.73 m
340 below MHW.

341***Precipitation and runoff data***

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

349Creek discharge peaked at 170 m³/s on December 12, 2014 when 40 mm of rain fell in a
35024-hour period.

351**Vertical accretion**

352*Mugu Lagoon*

353 Accretion and sediment parameters were low. Across the random plots, mean
354vertical accretion was 2 ± 0.3 mm/yr (mean $\pm$ SE, range 0-7 mm/yr; Table 1). Mean bulk
355density was 0.58 ± 0.15 g/cm³ (mean $\pm$ SE, range 0.24-0.92 g/cm³) and organic matter
356was $18 \pm 2.6\%$ (mean $\pm$ SE, range 5-42% (Table 1).

357 Accretion decreased from the edge of tidal creeks inland. Mean accretion was
358 2 ± 0.3 mm/yr at 3m from the tidal creek edge (mean $\pm$ SE, range 1-3 mm/yr; Table 1),
359 1 ± 0.3 mm/yr at 10 m (mean $\pm$ SE, range 0-2 mm/yr; Table 1), and 1 ± 0.4 mm/yr at 30 m
360(mean $\pm$ SE, range 0-3 mm/yr; Table 1). Mean bulk density was 0.68 ± 0.079 g/cm³ at 3 m
361from tidal creek edges (mean $\pm$ SE, range 0.54-0.90 g/cm³; Table 1), 0.56 ± 0.4 g/cm³ at 10
362m (mean $\pm$ SE, range 0.46-0.61 g/cm³; Table 1), and 0.49 ± 0.39 g/cm³ at 30 m (mean $\pm$
363SE, range 0.46-0.54 g/cm³; Table 1). Mean percent organic matter was $15 \pm 1.4\%$ at 3 m
364from tidal creek edges (mean $\pm$ SE, range 12-18%; Table 1), $19 \pm 5.6\%$ at 10 m (mean $\pm$
365SE, range 14-27%; Table 1), and $23 \pm 6.4\%$ at 30 m (mean $\pm$ SE, range 22-26%; Table 1).

366 The mean accretion rate of the random plots was not statistically different from
367the mean accretion rate of creek edge to inland transects. Furthermore, mean percent
368organic matter and mean bulk density values of the random plots were not statistically
369different than the values at 10 m from the edge of the tidal creek ($p > 0.05$). Patterns of
370percent organic matter and bulk density were the inverse of each other, as mean percent
371organic matter increased by 8% from 3 m to 30 m (although the difference was not

significantly different) and mean bulk density decreased by 26% from 3 m 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 ± 0.5 mm/yr (mean $\pm$ SE, range 1-10 mm/yr; Table 1). Mean bulk density was 0.67 ± 0.15 g/cm³ (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 ± 0.7 mm/yr at 3 m from tidal creek edge (mean $\pm$ SE, range 4-9 mm/yr; Table 1), 6 ± 1 mm/yr at 10 m (mean $\pm$ SE, range 3-9 mm/yr; Table 1), and 6 ± 3 mm/yr at 30 m (mean $\pm$ SE, range 0-18 mm/yr; Table 1). Mean bulk density was 0.65 ± 0.051 g/cm³ at 3 m from tidal creek edges (mean $\pm$ SE, range 0.47-0.81 g/cm³; Table 1), 0.61 ± 0.030 g/cm³ at 10 m (mean $\pm$ SE, range 0.50-0.69 g/cm³; Table 1), 0.49 ± 0.29 g/cm³ at 30 m (mean $\pm$ SE, range 0.29-0.78 g/cm³; Table 1). Mean percent organic matter was $10 \pm 1.3\%$ at 3 m from tidal creek edges (mean $\pm$ SE, range 5-14%; Table 1), $11 \pm 1.7\%$ at 10 m (mean $\pm$ SE, range 7-16%; Table 1), $17 \pm 5.1\%$ at 30 m (mean $\pm$ 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 m to 30 m and bulk density decreased by 25% 3 m 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 mean percent organic matter at 10 m from the edge of the tidal creek while mean bulk density in the

395 random plots was not significantly greater than mean bulk density at 3 m from the edge
396 of the tidal creek ($p > 0.05$).

397 *Sediment flux*

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

405 *Relationship of bulk density to percent organic matter*

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

412 ***Suspended Sediment Concentration***

413 *Mugu Lagoon*

414 Dry weather suspended sediment concentrations were low and similar within and
415 across sites. Across transects, dry weather suspended sediment concentrations during
416 flood tide were 37 ± 1.8 mg/L (mean $\pm$ SE, range 7-88 mg/L, $n = 120$), while mean percent

417 organic matter was $26 \pm 2\%$ (mean $\pm$ SE, range 0-100 %, n=120). Suspended sediment
418 concentrations were 51 ± 5 mg/L (mean $\pm$ SE, range 28 – 88 mg/L) at 0 m (n=12), 40 ± 6
419 mg/L (mean $\pm$ SE, range 7-76 mg/L) at 10 m (n=12), and 35 ± 5 mg/L (mean $\pm$ SE, range
420 11-59 mg/L) at 31 m (n=12) from the creek edge (Fig. 4). Percent organic matter was 16
421 $\pm 2\%$ (mean $\pm$ SE, range 0 – 25%) at 0 m (n=12), $24 \pm 4\%$ (mean $\pm$ SE, range 0 – 50%) at
422 10 m (n=12) and $25 \pm 7.7\%$ (mean $\pm$ SE, range 0 – 100%) at 31 m (n=12) from the edge.
423 Differences in suspended sediment concentrations and percent organic matter in these
424 monitoring stations were not statistically significant ($p > 0.05$).

425 Wet weather suspended sediment concentrations were high. For example during
426 flood tide values were 177 ± 15 mg/L (mean $\pm$ SE, range 31-649 mg/L, n=109), while
427 mean percent organic matter was $15 \pm 1\%$ (mean $\pm$ SE, range 0-33 %, n=109).
428 Suspended sediment concentration was 264 ± 61 mg/L (mean $\pm$ SE, range 79 – 618
429 mg/L) at 0 m (n=12), which was statistically different from the 31 m concentration ($D =$
430 0.6667, $p < 0.05$), but not the 10 m concentration. Suspended sediment concentration was
431 148 ± 30 mg/L (mean $\pm$ SE, range 38 – 312 mg/L) at 10 m (n=11) and 72 ± 8 mg/L (mean
432 $\pm$ SE, range 38 - 115 mg/L) at 31 m (n=8) from the edge (Fig. 5). Percent organic matter
433 was $14 \pm 1\%$ (mean $\pm$ SE, range 9 - 21%) at 0 m (n=12), $14 \pm 2\%$ (mean $\pm$ SE, range 0 -
434 27%) at 10 m (n=11) and $17 \pm 1\%$ (mean $\pm$ SE, range 13 – 24 %) at 31 m (n=8) from the
435 edge, although differences were not statistically different from each other ($p > 0.05$).

436 *Seal Beach Wetlands*

437 Across transects, dry weather suspended sediment concentrations were 41 ± 2
438 mg/L (mean $\pm$ SE, range 17-111 mg/L, n=90), while mean percent organic matter was 15
439 $\pm 1\%$ (mean $\pm$ SE, range 0-43 %, n=90). Suspended sediment concentration was 48 ± 2

440mg/L (mean $\pm$ SE, range 37 – 61 mg/L) at 0 m (n=9), 43 $\pm$ 3 mg/L (mean $\pm$ SE, range 32
441– 59 mg/L) at 10 m (n=9) and 39 $\pm$ 4 mg/L (mean $\pm$ SE, range 24 – 64 mg/L) at 31 m
442(n=9) from the creek edge (Fig. 4). Organic matter percent was 18 $\pm$ 2 % (mean $\pm$ SE,
443range 13 – 27%) at 0 m (n=9), 16 $\pm$ 3 % (mean $\pm$ SE, range 7-27%) at 10 m (n=9) and 15
444 $\pm$ 3 % (mean $\pm$ SE) at 31 m (n=9) from the edge.

445 While suspended sediment concentrations at 0 m were significantly greater than
446concentrations at 10 m and 31 m ($D=0.6296$, $p<0.05$), differences in suspended sediment
447concentrations at 10 m and 31 m were not significantly different ($p>0.05$). Furthermore,
448differences in measured values of percent organic matter were not statistically significant.

449*Relationship of organic matter to suspended sediment concentration*

450 Across all sites, at dry weather suspended sediment concentrations less than
451approximately 110 mg/L, there was an inverse relationship between suspended sediment
452concentrations and percent organic matter (Fig. 5). All suspended concentrations above
453110 mg/L were observed at Mugu Lagoon during wet weather, where the pattern of
454decline in percent organic matter was less steep compared to dry weather periods. When
455suspended concentrations were above 110 mg/L, mean percent organic matter was stable
456and remained below 33%.

457**Discussion**

458 Our objectives were to determine: (1) short-term salt marsh surface accretion rates
459for these two common types of southern California salt marshes; (2) the spatial patterns
460of accretion and suspended sediment concentrations; and (3) the impact of wet and dry
461weather, 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 to 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 run-off 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/100yr, a rate that is 43% greater than high SLR scenarios (1.7m/100yr) for this region (National Resource Council 2012). However, our coupled suspended sediment and accretion measurements at 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 to measured *Spartina*-dominated marsh accretion rates in Tijuana Estuary between 1992 and 1994, which ranged between 14mm/yr and 60mm/yr (Cahoon et al. 1996). However, the salt marsh accretion rates at

485Mugu Lagoon are slightly higher compared to the range of those observed in the
486*Salicornia*-dominated salt marsh from the same study (0.7-1.4mm/yr). The decline, from
487tidal creek to interior, although not statistically significant, was most apparent in creek
488edge to inland transects, which measured accretion and storm-related suspended
489sediments in Mugu Lagoon. This pattern suggests that the mineral sediment that is being
490delivered to the marsh is contributing to accretion along the creek edge at a higher rate
491than farther away from the creek.

492 While accretion at Seal Beach may be higher simply due to the fact that Seal
493Beach is lower in the tide frame, there could be an effect of channel area and density that
494warrants further investigation. In Seal Beach Wetlands, the decay from edge to interior
495was less apparent where samples were taken parallel to a creek that was an order of
496magnitude wider than the creek sampled at Mugu Lagoon. Furthermore, the backside of
497one transect at Seal Beach Wetlands approached a creek of similar width to that of Mugu
498Lagoon's main channel. Therefore, the larger channel area and increased channel
499density might be contributing to the high accretion rate at Seal Beach.

500 In the systems studied here, tidal creeks appear to play an important role in
501delivering turbid waters to the salt marsh plain via a watershed sediment source during
502run-off events; although, elevation and marsh age (Chen et al. 2016) may also drive the
503surface processes we observed. Although we did not measure elevation at individual plots
504at Seal Beach Wetlands, bulk density may have been higher in the random plots (Table 1)
505because transects were located in higher elevations (Fig 1). Across marsh differences in
506bulk density (higher at Seal Beach Wetlands) and organic matter (higher at Mugu
507Lagoon) may also be related to geomorphic and plant community differences. In the San

508 Francisco Bay Area salt marshes, Callaway et al. (2012) found that mineral accumulation
509 rates were higher at low-marsh stations within individual sites. In our study, distance to
510 tidal creek appears to influence bulk density and organic matter patterns in recently
511 accreted sediments.

512 Our results support the notion that point measurements of accretion rates and
513 suspended concentrations alone can be a misleading indicator of salt marsh stability
514 (Kirwan et al. 2008). Although the recent subsidence history for the salt marsh at Mugu
515 Lagoon is unknown, Seal Beach Wetlands has been subsiding between 2 and 8 mm/yr
516 since 1968. Subsidence at Seal Beach Wetlands is due to a combined effect of
517 groundwater, oil and gas extraction (Takekawa et al. 2014), which increases inundation
518 frequency and would potentially lead to higher accretion rates in order for the marsh plain
519 to maintaining equilibrium with sea level (Morris et al. 2002). Furthermore, if the pattern
520 of accretion is set by infrequent flooding events, then differences in dry weather
521 suspended sediment concentrations may not predict salt marsh resilience to sea level rise.

522 A better spatial and temporal understanding of sources and mechanisms of
523 sedimentation in highly modified marshes is needed to assess the vulnerability of these
524 salt marshes to sea-level rise. For example, Ganju et al. (2015) suggest using the
525 differential between flood and ebb tide SSC as an indicator of salt marsh stability. In a
526 mid-Atlantic salt marsh, an unstable salt marsh was characterized by an -18mg/L flood-
527 ebb differential. In Seal Beach Wetlands and Mugu Lagoon, Rosencranz et al. (2016)
528 observed the differentials of mean flood and ebb SSC to be approximately zero in two
529 channels at Seal Beach Wetlands and Mugu Lagoon. Conversely, another channel at Seal
530 Beach Wetlands had a flood-ebb differential that was -2mg/L. Given the balanced fluxes

531that have been observed in the system, relative to the large exports from the Mid-Atlantic
532salt marsh, we assume that the flood-ebb differentials are similar on the salt marsh plain
533in our study sites. However, suspended sediment samples during ebb tide are needed to
534confirm this.

535 Salt marsh resilience models, such as SLAMM and the Wetland Accretion Rate
536Model of Ecosystem Resilience (WARMER)(Swanson et al. 2013) apply a regional
537accretion rate to many sites (Zhang & Gorelick 2014), or accretion rates specific to marsh
538zone within a single site (Swanson et al. 2013). We found accretion rates were higher
539near creeks and at lower elevation sites on the marsh plain, although these relationships
540were not statistically significant. These patterns are being influenced by sediment
541delivery via large storm events. These results can be incorporated into spatially-explicit
542sea-level rise modeling efforts to help build a better understanding of salt marsh
543resilience to sea-level rise.

544**Conclusions**

545 This study enumerated patterns of accretion and suspended sediment dynamics in
546two representative southern California salt marshes of a Mediterranean climate. While
547both marshes appear to be keeping pace with current rates of sea level rise (National
548Resource Council 2012), the magnitude and patterns of mineral sediment concentration
549and accretion, along with no known recent elevation decreases at Mugu Lagoon
550(Rosencranz et al. 2016), suggest it may be the more resilient marsh under the low sea
551level rise scenario (4 mm/yr) – an optimistic projection for the region (Kopp et al. 2014).
552Despite high accretion rates, salt marshes at Seal Beach Wetlands, which are low in the
553tide 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

577rises, while Seal Beach Wetlands's accretion rate is likely at, or close to, its upper limit
578based on the low availability of mineral sediment due to a lack of watershed sediment
579source.

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 748 **172**:89-100.

Table 1 Accretion (mm/yr), bulk density (BD; g/cm³), and % organic matter (OM; mean ± SE). in surface samples at the central basin of Mugu Lagoon and Seal Beach Wetlands. 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/yr) for a 0.25 m² plot.

Site (location)	n	Accretion (mm/yr)	n	BD(g/cm ³)	n	OM (%)	Sediment flux (g/yr)
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 Beachs (30 m)	6	6±3	5	0.49±0.29	5	17±5.1	735

754Figure captions:

755Fig. 1. Regional map showing approximate size and location of watersheds (A and B;
756source: <http://nationalmap.gov/viewer.html>); and maps of Seal Beach Wetlands National
757Wildlife Refuge (Seal Beach Wetlands; C) and the central basin of Mugu Lagoon (D).
758White circles in C and D show singles or pairs of independent feldspar markers sampled
759at Seal Beach Wetlands (n=20) and Mugu Lagoon (n=41) that were randomly distributed
760throughout both marsh footprints; white stars show location of transects, while right
761column maps at Seal Beach Wetlands (E) and Mugu Lagoon (F) show locations of
762transects, where adjacent plots were at 3, 10, and 30 m from the edge of a tidal creek.
763Dashed white lines show approximate fixed point sampling location for suspended
764sediment concentrations which were established at 0, 1, 2, 3, 5, 8, 10, 15, 22, 31 m from
765the edge of the major tidal creeks (Rosencranz et al. 2015).

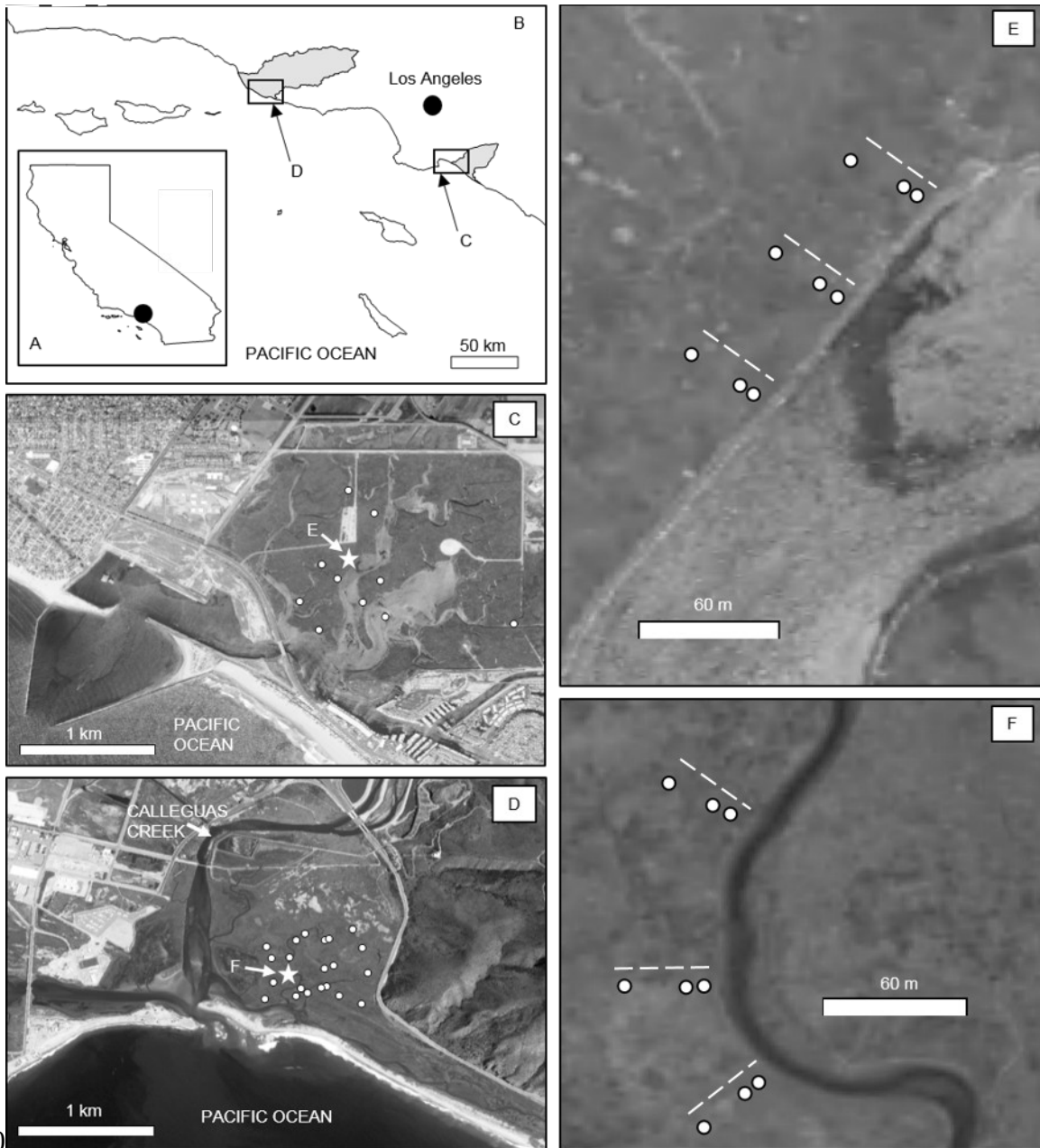
766Fig. 2. Daily average precipitation (mm) totals for Seal Beach Wetlands (top) and central
767basin of Mugu Lagoon (Mugu Lagoon; center). Bottom graph shows instantaneous
768discharge values (m^3/s) measured every five minutes for Calleguas Creek. Daily
769measurements of precipitation for Seal Beach Wetlands were retrieved from the
770California Irrigation Management Information System (CIMIS) site #174
771(<http://www.ipm.ucdavis.edu/>), which is 7 km north of the site. Daily measurements of
772precipitation for Mugu Lagoon were retrieved from CIMIS site #156
773(<http://www.ipm.ucdavis.edu/>), located approximately 17 km northwest of the site.
774Calleguas Creek instantaneous creek discharge measurements (m^3/s) were obtained from
775a stream gage upstream from Mugu Lagoon (<http://waterdata.usgs.gov/nwis>).

776Fig. 3. The relationship of bulk density (BD) and loss on ignition (LOI) in the Seal Beach
777Wetlands National Wildlife Refuge (left) the central basin of Mugu Lagoon (right).

778Fig. 4. The effect of distance to tidal creek on suspended sediment concentrations (mg/L)
779in the central basin of Mugu Lagoon (Mugu Lagoon) during a storm (February 27 to
780March 2; top), in Mugu Lagoon during dry weather (center), and in Seal Beach Wetlands
781(bottom). Highest suspended sediment concentrations were found within the first 10 m of
782the edge of tidal creeks. Error bars represent $\pm$ SE (n=3). Original data from Rosencranz et
783al. (2015).

784Fig. 5. The relationship of natural log of suspended sediment concentration (SSC) to
785natural log of percent organic matter for the central basin of Mugu Lagoon (Mugu
786Lagoon) during a storm (February 27 to March 2); at Mugu Lagoon during dry weather;
787and at Seal Beach Wetlands National Wetlands during dry weather. Original data from
788Rosencranz et al. (2015)

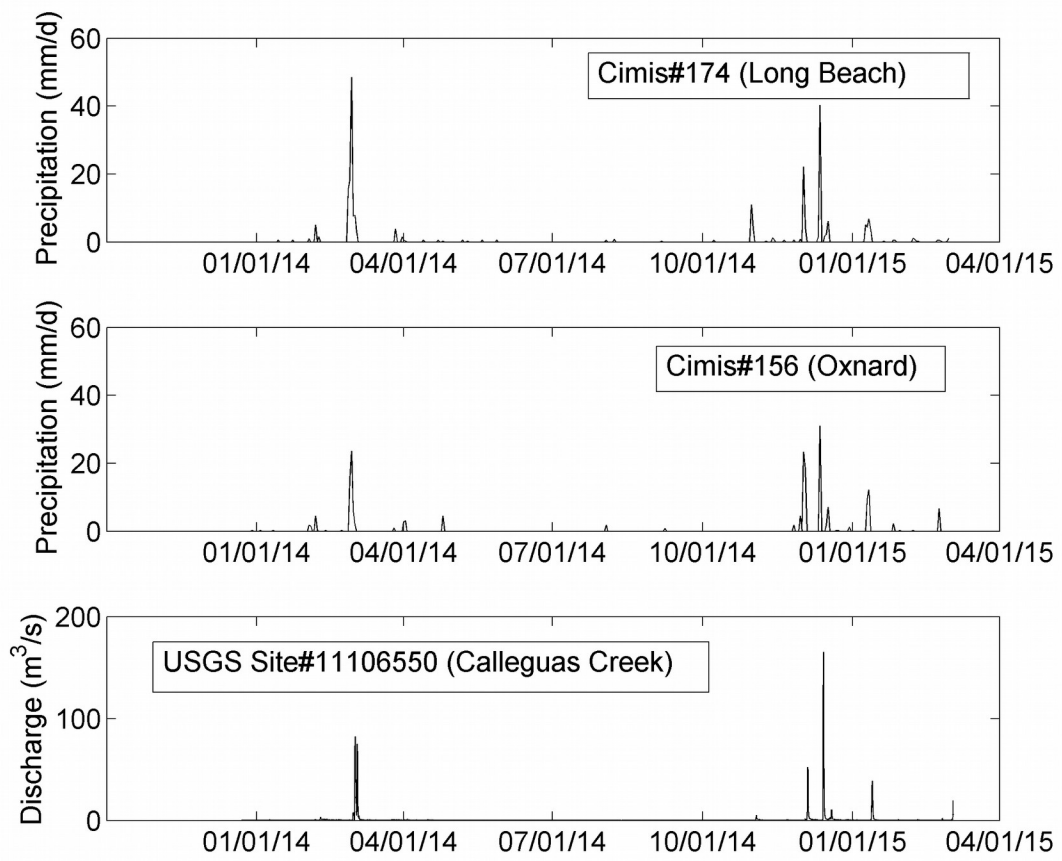
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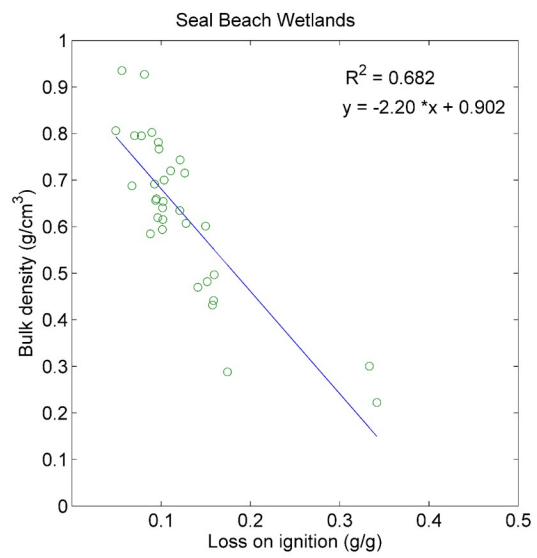
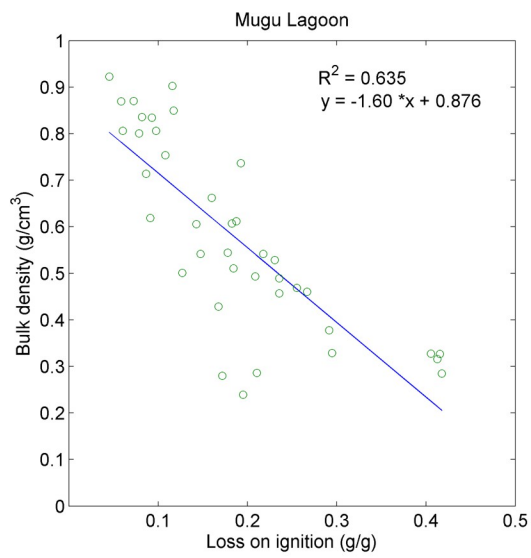
791**Fig. 1**

792

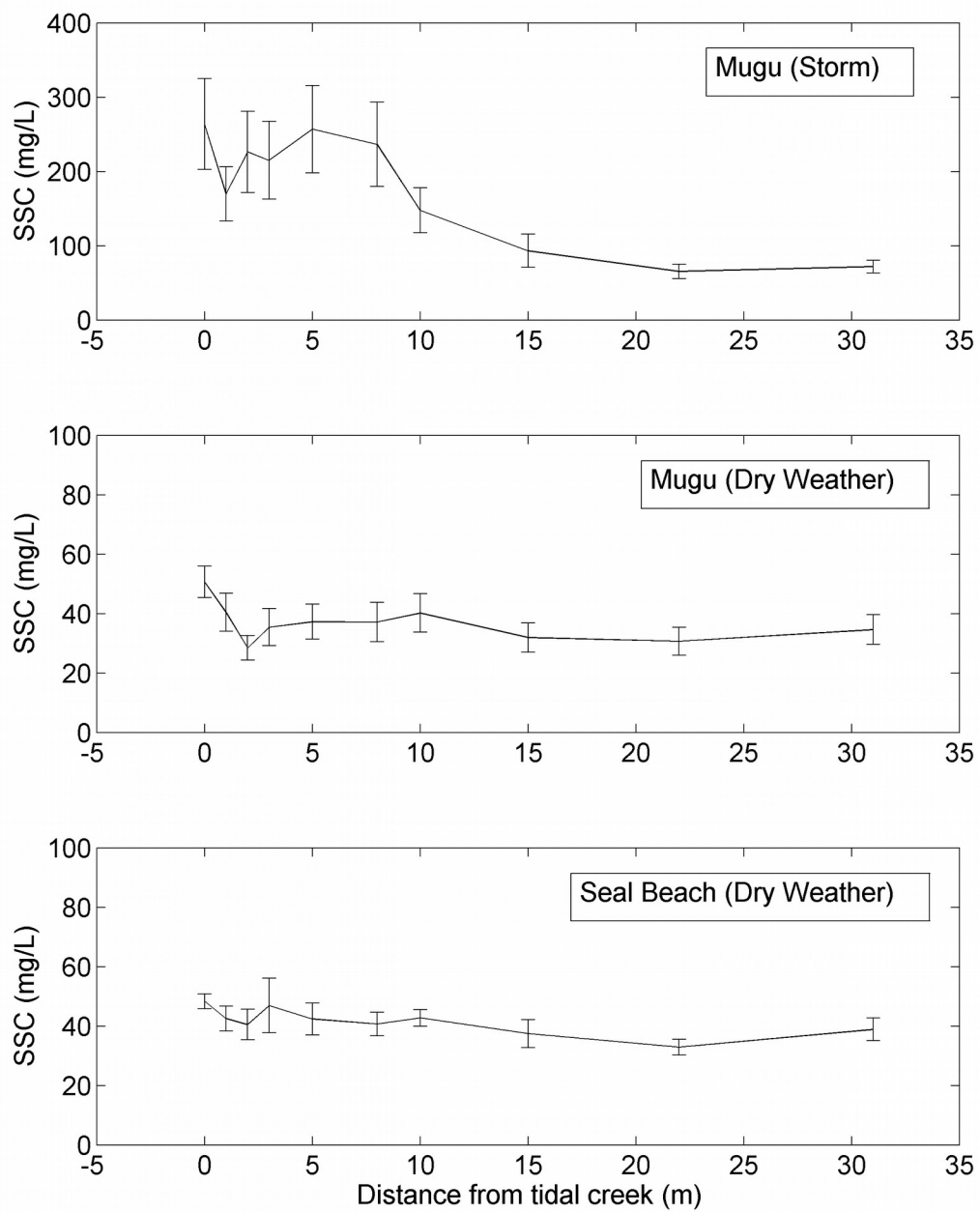


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794**Fig. 2**

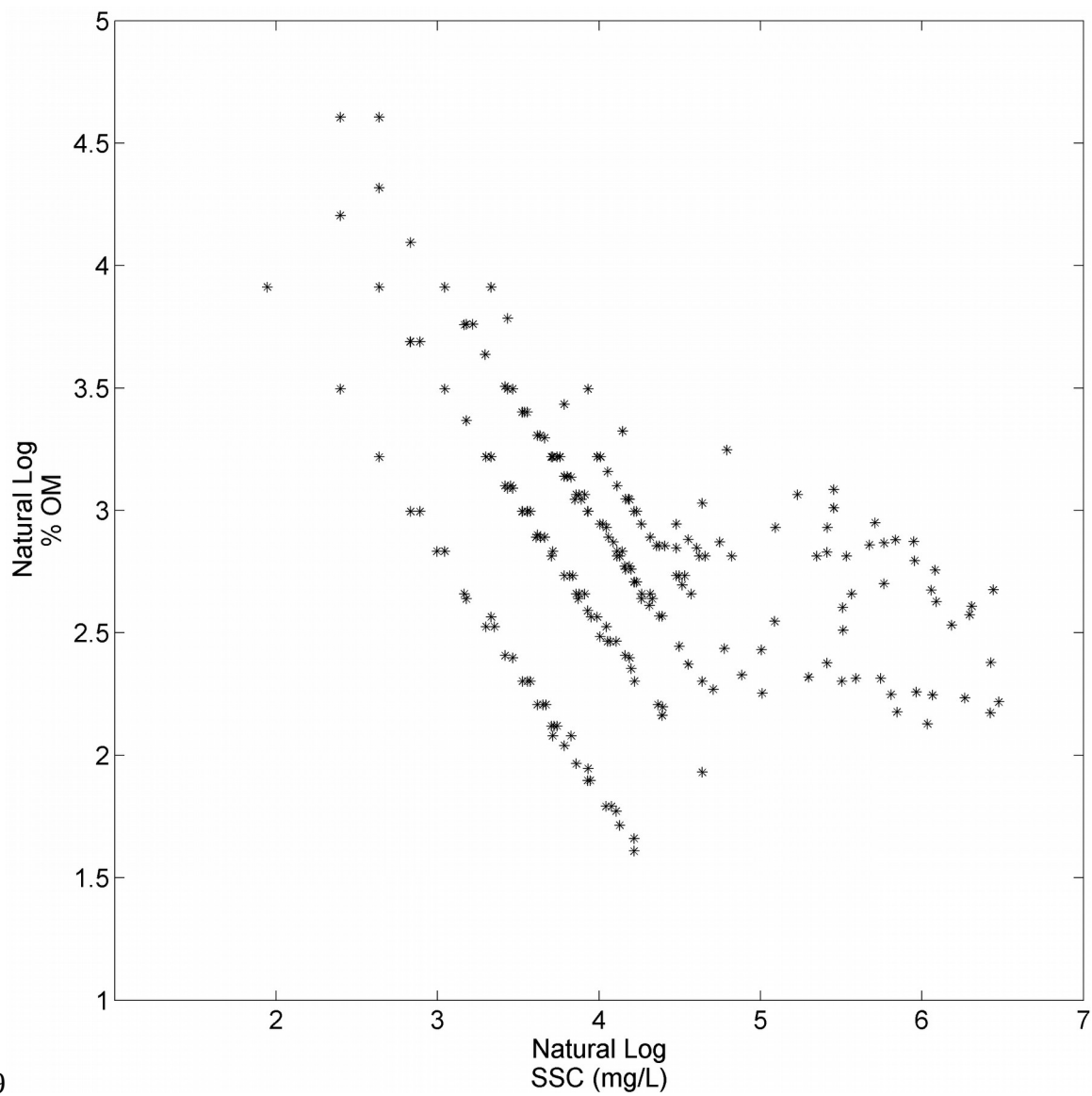


796**Fig. 3**



797

798**Fig. 4**



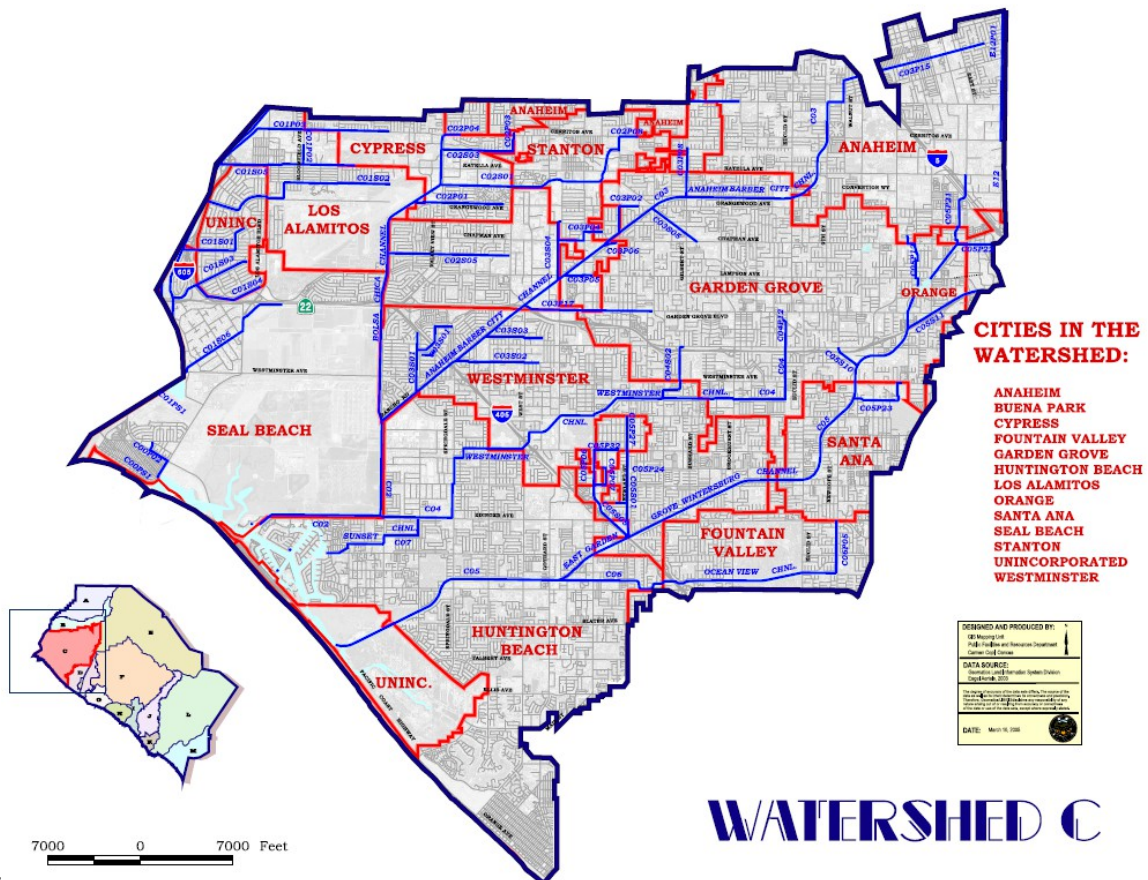
799

800**Fig. 5**

801

802Appendix 1: Map of flood control channels in the Catchment of Seal Beach

803Wetlands.



805Figure 1. Watershed map showing different flood control channels that may provide

806sediment to Seal Beach Wetlands (Source:

807<http://www.ocflood.com/civicax/filebank/blobdload.aspx?blobid=32723>)

808

809