

1 Effects of the 2015-2016 El Niño on Water Levels in Southern California Estuaries and
2 Implications for Elevated Sea-levels

3 Currently under review at Estuaries and Coasts

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37 **1 Abstract**

38 The 2015-2016 El Niño provided insight into how estuaries in Southern California might
39 respond to future conditions, including high offshore ocean temperatures, sea-levels, and wave
40 heights. Low rainfall totals during the 2015-2016 winter provided the opportunity to examine
41 how extreme ocean forcing impacts estuaries independently from fluvial events. From October
42 2015 to May 2016, water levels were continuously measured in 13 estuaries in Southern
43 California. The observed systems included both intermittently and perennially open estuaries

44 with varying watershed size, urban development, and management practices. Elevated water
45 levels offshore (due to the combined effects of surge, tides, wave setup, and higher sea-levels)
46 caused raised water levels and prolonged inundation in all of the estuaries studied. Water levels
47 inside perennially open estuaries mirrored offshore water levels, while water levels inside
48 intermittently open estuaries (IOEs) were nonlinearly elevated beyond the heightened offshore
49 water levels. Several of the IOEs closed when sand (driven into the inlet by wave-induced
50 sediment transport) accreted forming a barrier berm at the mouth. Closures were more persistent
51 and occurred in more estuaries than a typical year due to the elevated water levels and large
52 wave events. Understanding how coastal estuaries respond to increased sea-levels and the factors
53 that predict closures in specific estuaries will help managers, scientists, and agencies develop and
54 implement adaptation strategies.

55 **2 Introduction**

56 Estuaries and associated wetlands provide extensive ecosystem functions and services, including
57 biodiversity support, carbon sequestration, water quality improvement, and abatement of
58 flooding functions (Zedler and Kercher 2005; Takekawa et al. 2011; Homquist et al. 2018).
59 Under the growing threat of climate change, it is important to understand how such systems will
60 respond and adapt. In particular, the balance between the resiliency of wetlands to local sea-level
61 rise and their role in mitigating the effects of sea-level rise is not well understood (Shepard et al.
62 2011). This is especially true in traditionally under-researched systems such as low-inflow
63 estuaries (LIEs) typically found in Mediterranean climates. LIEs receive smaller and more
64 episodic freshwater inputs than their “classical” counterparts found in wetter climates with larger
65 watersheds (Largier et al. 1997; Ranasinghe and Pattiaratchi 2003; Behrens et al. 2013; Rich and
66 Keller 2013; Williams and Stacey 2016).

67 In Southern California, all estuaries are classified as LIEs and are threatened by both continued
68 urbanization and climate change. Nonetheless, these systems are extremely important to the
69 regional economy and ecology (Zedler and Kercher 2005; California Natural Resources Agency
70 2010). More than 100 estuaries line the highly urbanized Southern California coastline (Doughty
71 et al. in press), all with varying degrees of physical modifications, including the damming and
72 channelizing of river inflows; the construction of breakwaters and jetties at inlets; the dredging
73 of channels, inlets, and harbors; the construction of roads splitting systems; and the destruction
74 of wetlands (e.g., Pratt 2014; Los Peñasquitos Lagoon Foundation et al. 2017).

75 Historically, most LIEs in Southern California are estuaries that would occasionally close
76 (intermittently open estuaries, IOEs) (Jacobs et al. 2010) by sediment driven into the mouth by
77 waves and currents and accreting to form a sill or barrier berm (e.g., Elwany et al. 1998; Behrens
78 et al. 2013; Rich and Keller 2013). In IOEs, during low tides, estuarine water levels are perched
79 above the offshore water levels due to hydraulic control at the sill. When the mouth is open and
80 the offshore water level is below the sill elevation, these systems slowly drain until the offshore
81 water level is once again above the sill and the tide flows into the estuary (e.g. Williams and
82 Stacey, 2016). Today, many of these systems are managed to maintain an open state either
83 through dredging, infrastructure, or some combination of methods (perennially open estuaries,
84 POE).

85 As communities and coastal managers develop Climate Action Plans and restoration programs
86 (e.g., San Elijo Lagoon Conservancy AECOM 2016; Los Peñasquitos Lagoon Foundation et al.
87 2017), there remain several critical questions as to how these systems will respond to rising sea-
88 levels and a changing climate, including if marsh accretion rates will keep pace with sea-level
89 and how elevation and formation of barrier berms will change. Recent work has begun to answer

90 these questions (Thorne et al. 2018; Doughty et al. in press), but a key unresolved issue is
91 whether IOE closures will become more prevalent in the future and what management
92 implications that may have.

93 The 2015-2016 El Niño provided an opportunity to assess how estuaries might respond to coastal
94 conditions predicted with climate change and sea-level rise. El Niño conditions in Southern
95 California are typically associated with increased storms, increased water levels, and large wave
96 events (e.g., Bromirski et al. 2003; Ludka et al. 2016; Barnard et al. 2017) which may become
97 more common in the future (Cayan et al. 2008). During the El Niño, anomalously large waves
98 were recorded all along the Southern California coast (Flick 2016; Ludka et al. 2016; Barnard et
99 al. 2017; Young et al. 2018). Additionally, offshore water levels were persistently above average
100 throughout the winter (Figure 2a, Sup. Figure 1) due to a combination of large scale atmospheric
101 and ocean forcing (e.g., Enfield and Allen 1980; Chelton and Davis 1982). Throughout Southern
102 California during the 2015-2016 winter precipitation was near or below average (e.g. Siler et al.
103 2017; Lee et al. 2017). The low rainfall totals during the 2015-2016 winter provide an
104 opportunity to examine how anomalous ocean forcing impacts estuaries independently from
105 fluvial events.

106 Previous work by Young et al. (2018) focused on how the 2015-2016 El Niño impacted the
107 coastal morphology of cliffs, beaches, and estuary mouths but did not examine the effects of
108 closures on water levels. The study found that on average, estuary inlets accreted over the course
109 of the winter. Moreover, some estuaries experienced anomalous mouth conditions including Los
110 Peñasquitos Lagoon (LPL) which closed for more days than it had in the past 25 years (Young et
111 al. 2018 building off Hastings and Elwany 2012) and the Tijuana River Estuary (TRE) which
112 closed for the first time since the previous large El Niño in 1982-1983 (Young et al. 2018).

113 This paper will focus primarily on how anomalous ocean forcing during the 2015-2016 El Niño,
114 particularly enhanced water levels and extreme water level events, affected LIEs of varying inlet
115 morphology. We address hypotheses proposed by estuary managers and scientists at various
116 management meetings that IOEs will respond differently to offshore water levels than POEs, that
117 percentage of marsh coverage in a system will impact the response of water levels, and that
118 systems more exposed to offshore wave energy will have a larger water level response than more
119 protected systems. I

120 **3 Methods**

121 **3.1 Summary of estuaries studied**

122 In this study, measurements were conducted in 13 estuaries (Figure 1) of varying mouth
123 morphology, size, marsh cover, and wave exposure along the Southern California Bight. Of
124 these systems, six estuaries are classified as intermittently open (IOE) or bar-built estuaries:
125 Mugu Lagoon, Malibu Lagoon, Santa Margarita Estuary, San Dieguito Lagoon, Los Peñasquitos
126 Lagoon (LPL), and Tijuana River Estuary (TRE). Seven systems are perennially open (POE) due
127 to mouth management including dredging and/or stabilization: Colorado Lagoon, Los Cerritos,
128 Alamitos Bay, Seal Beach, Newport Bay (NB), Agua Hedionda, and San Diego Bay (SDB). In
129 our definition of IOE versus POE, it is important to note that most of the estuaries included here
130 would have been IOEs under pre-development; thus here we refer to POEs as estuaries whose
131 mouths have been structurally altered (jetties, groins, revetments, etc.) to be perennially open.
132 The estuaries in this study are relatively small systems (14-2,050 acres, Table 1) with the
133 exception of San Diego Bay (~15,000 acres). Generally, IOEs have a higher percentage of marsh
134 cover than POEs (Appendix A). Some systems that straddle these definitions include ones such

135 as the San Dieguito Lagoon where some engineering as well as maintenance dredging ensures
136 the estuary is open, yet it still experiences significant morphological alterations near its mouth
137 during a season and is at risk for closure. Here, because of its large morphological changes at the
138 mouth and clear influence of the sill, we include San Dieguito Lagoon with the IOEs.

139 **3.2 Data Collection Techniques**

140 **3.2.1 Water Level Data**

141 Coastal water level measurements (6-minute interval) were extracted from the San Diego Bay,
142 La Jolla, Los Angeles, and Santa Monica National Oceanic and Atmospheric Administration
143 (NOAA) tide gauges (tidesandcurrents.noaa.gov Station IDs: 9410170, 9410230, 9410660, and
144 9410840). Estuarine water levels were measured by various agencies as part of ongoing
145 monitoring programs across the region, with sampling intervals ranging from 2 seconds to 30
146 minutes. Loggers included Teledyne RDI ADCPs (acoustic Doppler current profilers), Hobo
147 pressure loggers, Sea-Bird CTDs (conductivity, temperature, depth), YSI 6600, EXO2
148 multiparameter sondes, Design Analysis Associates Inc. WaterLOG Microwave sensor, and
149 RBR pressure loggers. Barometric pressure corrections were performed (Section 3.2.3), and
150 pressure data was converted into water depth. All available data provided by agencies during the
151 primary study period, November 1, 2015 to April 1, 2016 were used. Additionally, to provide
152 historical context, data collected from 2005 to 2018 in LPL, TRE, and SDB were analyzed.
153 Specific estuary data collection sampling schemes, quality control choices, instruments, and
154 locations are outlined in Appendix A. Open inlet periods in the IOEs were determined by
155 examining water level records. When available, satellite imagery data from Planet.com and/or
156 mouth imagery (Appendix A) were used to verify mouth state.

157 Absolute height (relative to a fixed geodetic datum, NAVD88) of loggers was only known at six
158 locations (Mugu Lagoon, Seal Beach, San Dieguito Lagoon, LPL, SDB, and TRE), where the
159 sensor elevations were surveyed during the study period. Therefore, to provide a consistent
160 relative datum (NAVD88), higher-high estuary water levels during open inlet phases were
161 adjusted to match higher-high water levels at the nearest NOAA tide gauge. The tidal phasing
162 differences between the estuary and tide gauge are preserved. This process assumes there is no
163 additional set-up or tidal dampening in the estuaries, which is a good estimate for these estuaries
164 because they are short relative to the tidal excursion (Friedrichs, 2010). Only the highest tide is
165 matched because it is least likely to be affected by frictional effects (e.g. Williams and Stacey
166 2016) and has been shown to be similar to predicted high tides in similar systems (Hubbard
167 1996). For the six stations with absolute elevation, testing this correction resulted in -0.04 m, -
168 0.01 m, -0.08 m, -0.01 m, -0.02 m, -0.06 m offsets (Mugu, Seal Beach, San Dieguito Lagoon,
169 LPL, TRE, and SDB respectively). These offsets are within the vertical error of real time
170 kinematic network rover (RTK GPS) surveying equipment used, indicating this method is
171 appropriate for converting all water level data into the NAVD88 datum.

172 Water levels were subsampled to 15 minutes and subtidal water levels were calculated using a
173 Godin filter (a low-pass filter that removes diurnal and higher frequency tidal energy) (Walters
174 and Heston 1982; Thomson and Emery 2014). In Mugu and Malibu Lagoons, the sensors were
175 deployed above lower-low water and were dry during the low tides. For these time periods, the
176 low-pass filtering biased the subtidal estuary water level high.

177 **3.2.2 Wave Data**

178 Offshore wave statistics were provided from the Coastal Data Information Program (CDIP) buoy
179 network (cdip.ucsd.edu). Nearshore wave statistics including significant wave height and peak

180 wave direction were extracted from the CDIP Monitoring and Prediction (MOP) System model
181 output (O'Reilly and Guza 1993; O'Reilly et al. 2016; cdip.ucsd.edu 2017). MOP uses a
182 numerical wave model to propagate deep-water buoy observations to the 10 m isobath
183 approximately every 100 m in the alongshore. All hindcast data were reported hourly. The
184 nearest MOP line to either the given NOAA tidal gauge or center of the estuary mouth is used for
185 each respective site as labeled in Appendix A.

186 **3.2.3 Atmospheric Data**

187 Barometric data used were from either the nearest NOAA weather station or airport, or pressure
188 sensor deployed at the estuary as specified in Appendix A. Precipitation data were from airport
189 stations. Weather stations used are marked on Figure 1.

190 **3.2.4 Berm Heights**

191 High-resolution topo-bathymetry transects were conducted at LPL using a Spectra Precision
192 Promark 700 GNSS real time kinematic network rover (RTK GPS) and Scripps Orbit and
193 Permanent Array Center (SOPAC) base station (SIO5) corrections. Eleven surveys conducted
194 between November 1, 2015 and April 1, 2016 in the case study site, LPL, are presented. Surveys
195 were performed manually at lower-low tides following radial transects around the curving lagoon
196 inlet. Measurements were not collected if the water level was greater than 1 m, or if the seafloor
197 substrate or tidal currents inhibited data collection. The average sill height elevation was
198 calculated by averaging either the beach area (west of the 101 bridge), the estuary area (area to
199 the east of the bridge excluding the manmade berm) as indicated in Supplementary Figure 3). To
200 determine sill changes over shorter time periods, we extracted the estuary lower-low water level
201 as a proxy for sill height and validated it against our topo-bathymetric surveys. Imagery from

202 time-lapse cameras installed near the mouth were used to qualitatively assess the migration and
203 accretion of the sill over time.

204 4 Results

205 4.1 Offshore Conditions During 2015-2016 El Niño

206 Southern California water levels were persistently above average throughout the strong 2015-
207 2016 El Niño (Figure 2a, Sup Figure 1). The maximum monthly average offshore water levels
208 were 0.20 m, 0.20 m, and 0.21 m above the predicted levels for La Jolla, Los Angeles, and Santa
209 Monica respectively (La Jolla in Figure 2a). Offshore, the largest waves were predominantly
210 from the northwest, thus the southern estuaries were more exposed to offshore wave forcing due
211 to the geometry of the coast and effect of islands within the California Bight (Figure 1).

212 The maximum offshore subtidal water levels during the study period occurred during extreme
213 wave events and were 0.31 m, 0.30 m, and 0.31 m above the NOAA predicted subtidal water
214 levels for La Jolla, Los Angeles, and Santa Monica respectively (Figure 2a). High subtidal water
215 levels were due to a combination of atmospheric forcing, storm surge, and large waves events.

216 Winter coastal water levels were correlated with both the Godin filtered significant wave heights
217 ($r = 0.39, 0.33, 0.28$ with -1.2, -1.3, -1.1 day lag) and the barometric pressure ($r = -0.72, -0.67, -$
218 0.73 with -0.0, -0.2, -0.2 day lag). The high correlation with barometric pressure is likely due to
219 a combination of the effects of storm surge, waves, and changes to local offshore winds and
220 currents caused by local storms.

221 In San Diego, there were seven precipitation events with rainfall over 10 mm per day (2 d). The
222 total precipitation at San Diego Airport during the winter of 2015-2016 was about 21 percent
223 below average (40th percentile of the winter historical rainfall totals from 1939 to 2018) [NOAA

224 National Climatic Data Center, Station ID: USW00023188]. This lower than average rainfall is
225 consistent with XXXXX

226 **4.2 Estuary water levels**

227 ***Representative POEs: San Diego Bay and Newport Bay***

228 In SDB and NB, the maximum tidal ranges were 2.62 m and 2.52 m, respectively during the
229 primary study period. In these systems both the instantaneous (Figure 3a, light blue line from
230 NB) and subtidal water levels (Figure 3b, dark blue line from NB) were correlated with the
231 offshore water levels (Table 1) throughout the 2015-2016 winter. The strong correlations
232 between offshore and estuarine water levels in SDB were consistent with those found in a
233 historical comparison of SDB with offshore water levels (Figure 5 a-b).

234 ***Representative IOEs: Tijuana River Estuary and Los Peñasquitos Lagoon***

235 In both TRE and LPL, sills comprised of sand and cobbles grew over the 2015-2016 winter and
236 restricted flow or closed the respective inlets for brief periods of time (discussed further in
237 Sections 4.3 and 4.4). During the open states, hydraulic control at the sills contribute to
238 elongated and truncated ebbs (example from LPL shown in Figure 3a, yellow line relative to
239 orange). The sills resulted in reduced tidal ranges (1.55 m and 1.37 m, for TRE and LPL
240 respectively) compared with offshore ranges and contributed to low correlations between
241 offshore and estuarine water levels (r^2 values $< .4$, Table 1). As a result of the lower-low tide
242 truncation and perching, subtidal water levels in TRE and LPL (LPL is yellow in Figure 3b)
243 were higher than offshore water levels. The LPL and TRE subtidal water levels exhibited a non-
244 linear and amplified response to high offshore water levels (i.e., for a given offshore water level,
245 estuarine water levels were higher, see Figure 5) for tidal and subtidal water levels, a trend

246 consistent in a historical analysis (2005-2018, see Figure 5). Using the historical record (2005 –
247 2018), while analysis of water levels compared with wave energy was complicated by several
248 factors including river flow, sill height, and importantly, dredging, elevated water levels in LPL
249 and TRE were more frequently observed during years with larger waves when comparing the
250 effects of large waves and offshore water levels (Sup Figure 2).

251 *Comparison of Water levels in IOEs and POEs*

252 Mean subtidal water levels for the observation period were highest in the IOEs that closed;
253 followed by in the IOEs that remained open for the study period, with the POEs maintaining the
254 lowest mean water levels (Figure 4, Table 1). In Mugu and Malibu, the sensors were dry at the
255 low tides causing the average water levels to be biased high.

256 During open periods, most of the IOE subtidal water levels had a higher variance than POE
257 subtidal water levels (Table 1, Figure 6), indicating that the water levels in IOEs had a more non-
258 linear response to offshore elevated water levels and large wave events. The instantaneous water
259 levels in the POEs are more strongly correlated with the offshore water levels than the IOEs
260 (Table 1 and Figure 5).

261 **4.3 Estuary Closures**

262 During complete inlet closures, water levels increased because the sill blocked outflows while
263 inflows from freshwater upstream continued (see for example LPL in Figure 3 and other IOEs in
264 Figure 4). In addition, in some circumstances, large wave overtopping contributed to increased
265 water levels behind the sill which we can deduce from time-lapse imagery and high frequency
266 pressure measurements. During the observation period, Malibu Lagoon was closed for 30 days
267 and naturally reopened; LPL was closed for 36 days, naturally reopened once and was

268 mechanically breached three times; TRE was closed for 13 days (starting at the end of the study
269 period) and was mechanically breached; Santa Margarita Estuary was closed for 44 days and
270 naturally reopened.

271 **4.4 Sill Height Changes over Time in Los Peñasquitos Lagoon**

272 LPL experienced 0.5 to 2 meters of accretion (Figure 6c) in the inlet region over the course of
273 the winter season, in addition to nearly 1 m of erosion of a man-made berm protecting the
274 estuary marsh further upstream. Although measurements were not taken at a high-enough
275 frequency to capture changes on the time scales of tides or storms, time-lapse imagery and in-
276 person observations show that the channel migrated between harden structures and that the sill
277 migrated within the inlet area and changed elevation throughout the study period. Importantly,
278 imagery indicates that inlet accretion occurred episodically and typically coincided with periods
279 of large offshore waves.

280 Before the estuary closure, the average height of the estuary area (Sup Figure 3, purple)
281 correlated strongly with the lower low water levels (Figure 7b,). Immediately before closure, the
282 height of the beach area more closely matched lower-low water level because the large sill
283 accreted just west of the Highway 1 Bridge. Overall, the estuary lower-low water level decently
284 matched the average sill elevation as measured by the topo-bathymetric surveys (Figure 7b, blue)
285 ($r^2=0.83$, RMSE = 0.19 m). These results indicate that we can use lower-low water levels to
286 approximate elevation changes of the sill over time and can examine the interactions between sill
287 height and offshore water levels.

288 **5** **Discussion**

289 **5.1 El Niño and Implications to Future Conditions**

290 During the 2015-2016 El Niño, elevated offshore water levels (Figure 2a) and low precipitation
291 (Figure 2c) provided the opportunity to understand how small LIEs respond to oceanic forcing.

292 The sea-level anomaly associated with the 2015-2016 El Niño in La Jolla is comparable to the
293 amount of sea-level rise likely to occur by 2030 (Griggs et al, 2017), with some estimates of
294 much higher rates of sea-level rise possible (e.g., Sweet et al. 2017). As described in more detail
295 in Young et al. 2018, although modeling suggests that storm tracks are projected to shift pole-
296 ward resulting in decreased waves in the Southern California Bight (i.e. Erikson et al. 2016,
297 Graham et al., 2013) there is nonetheless likely to be an increase in extreme water levels due to
298 rising seas alone in Southern California (Tebaldi et al. 2012; Sweet and Park, 2014).

299 Additionally, while difficult to predict, there is some suggestion of more frequent El Niño events
300 (Cai et al. 2014) with a changing climate. Therefore, these estuaries will experience more
301 extreme water level events in the future and possibly more frequent El Niño conditions.

302 **5.2 Morphodynamics in IOEs**

303 Significant morphological changes near the mouth were observed in most of the IOEs during the
304 observation period (as evident from increasing lower-low water levels and time-lapse imagery).

305 The enhanced sill accretions and more frequent and persistent closures observed in IOEs in
306 Southern California during the 2015-2016 El Niño season (as presented here and from a different
307 dataset in Young et al. 2018 which built off Elwany et al. 1998) can be attributed to the
308 anomalously large wave conditions coupled with anomalously low precipitation, as expected
309 from the Behrens et al. (2013) model of inlet accretion. In both LPL and TRE, multi-year water

310 level records indicate that sill heights generally increased during large wave events and
311 decreased during significant flushing events. Additionally, years with larger wave events were
312 years with higher estuarine water levels, higher sills, and more closure days (Supplementary
313 Material, 2). Unfortunately, sparse data and periodic dredging precluded further analysis. In the
314 four southern IOEs, the sill heights grew during the largest wave events during this study.

315 Large waves and the alongshore migration of beach nourishment sand (Ludka et al. 2018) are
316 likely responsible for the 2016 closure at TRE. Both TRE and LPL were artificially breached
317 during the 2015-2016 El Niño; had the systems not been breached, the water levels in the
318 systems would have been elevated for an even more prolonged period.

319

320 **5.3 Comparison of IOEs and POEs**

321 This paper represents one of the first times (to the authors' knowledge) water levels from such a
322 wide range of systems in Southern California were measured, analyzed, and compared over the
323 same timeframe. The subtidal water levels in POEs mirrored offshore water levels both in mean
324 water level and variance while the subtidal water levels in IOEs were higher on average and had
325 a higher variance. The mean water levels in the IOEs were higher because the sill height at the
326 mouths of IOEs dictates the lower-low water level and thus the subtidal and average water levels
327 in these systems. Overall, IOEs have a more non-linear response to high offshore water levels
328 than POEs, a result that our data suggests is largely due to mouth morphology, and to a lesser
329 extent, geometry, including system size, depth, and marsh area (Friedrichs 2010).

330 Decoupling the effects of marsh extent and mouth morphology with this limited dataset is
331 challenging because in Southern California, IOEs are generally more natural systems with higher

332 percentages of marsh while POEs are more heavily managed and channelized (Appendix A). The
333 overall trends seen in Figure 6 are consistent with the hypothesis that the percentage of marsh
334 extent impacts water levels inside of these estuaries (with more marsh leading to higher water
335 levels). However, in a direct comparison between estuaries with similar percentages of marsh
336 habitat (Appendix A), it appears that mouth morphology (i.e., the presence/absence and size of a
337 sill) plays a more important role in setting the mean estuarine water levels.

338 Assessing contributions from and decoupling the different components of the total water level
339 (e.g., waves versus barometric pressure versus longer term elevated offshore water level effects)
340 was also difficult with this dataset. In particular, plots of estuarine water level versus wave
341 height (not shown) hint at IOEs having a greater response to large waves; however, the
342 geographical location of IOE and POEs complicates this assessment as the geometry of
343 California Bight dictates the amount of wave energy (MOP wave roses, Figure 1) and the peak
344 wave direction at the estuary mouth. Nearly all POEs are to the north, where the waves at their
345 mouths were smaller during this study due to regional shadowing. The only POE exposed to
346 large waves is Agua Hedionda where a shorter dataset limits the number of large wave events to
347 only one (only 1 event where $H_s > 2$ m for more than 1 hour). Additionally, Agua Hedionda
348 experienced some inlet accretion over this study period, likely resulting from its exposure to
349 larger waves. Thus, due to the geometry and island of the California Bight (Figure 1), geographic
350 location and wave shadowing play a large role in the wave conditions seen at the estuary mouth.
351 Nevertheless, when examining historical water levels at available locations, conditional
352 averaging based on wave heights resulted in higher IOE water levels than conditional averaging
353 based on total water level anomaly or river flow.

354 **5.4 Southern California Estuary Management Implications**

355 Open questions in the management strategy of these relatively small LIEs include how sea-level
356 rise will impact marsh elevation and tidal prism. The effects of sea-level on marshes (e.g.,
357 changes in accretion, migration, species composition, etc.) are currently a focus of several
358 studies (e.g., Thorne et al. 2016). Assuming that continued dredging and jetties at POE mouths
359 maintain current bed elevations as sea-level rises, it is expected that water levels in the POEs will
360 increase proportionately because POE water levels mirror offshore water level fluctuations and
361 tidal prism would increase. In IOEs however, the subtidal water level response depends on the
362 feedbacks between offshore water level increases and a variety of mechanisms including marsh
363 accretion, tidal prism, mouth morphodynamics, precipitation, and wave action. Any change in
364 tidal prism is dependent on both the sill height and the change in water elevation. Use of lower-
365 low water levels as an estimate of sill height (as described and validated in section 4.4) may be a
366 way to monitor the changing sill height over time. Even so, it is difficult to separate sill height
367 fluctuations (and thus tidal prism changes) from sea-level fluctuations because higher sea-levels
368 tend to occur during years of higher wave heights (El Niño years), thus continued observations
369 are required.

370 If closures become more frequent under future conditions as they did during the El Niño, the
371 estuaries would be subjected to more inundation of freshwater on saline or brackish habitats,
372 more frequent hypoxic conditions, longer periods of inundation at a fixed elevation, and pose a
373 greater risk for upstream flooding. For example, it has been observed that more frequent inlet
374 closures cause a shift from more saline marsh vegetation to more freshwater vegetation as the
375 surface layer over the marsh is fairly fresh (Los Peñasquitos Lagoon Foundation 2017).

376 Additionally, reduced tidal prism would cause physiologically stressful conditions and a

377 reduction of incoming marine propagules leading to changes in species composition and an
378 overall reduction in diversity of plants and animals (Teske and Wooldridge 2001; Phlips et al.
379 2002; Raposa 2002; Saad et al. 2002). During the 2015-2016 El Niño, mouth closures in TRE
380 and LPL resulted in hypoxia and subsequent fish kills within days. Similarly, sustained high
381 water in NB resulted in die-off of high marsh habitat that has been used as past nesting habitat
382 for several sensitive bird species (Dick Zembal, personal observations). The risk for upstream
383 flooding and inundation - including nearby infrastructure - increases during closures as the
384 estuaries slowly fill with upstream incoming fresh water and wave overtopping.

385 LIEs in Southern California (and around the world) are all managed by different entities with
386 varying priorities, stakeholders, and economic and ecological values (e.g. Pratt 2014; Zedler and
387 Kercher 2005). As different management entities develop Climate Action Plans for their
388 respective systems, they must take sea-level rise into account. This study demonstrates that water
389 level response (and therefore appropriate management strategies) will vary by system. In more
390 perennially open systems, near the mouth it is expected that the water levels will continue to
391 match the water levels offshore with upstream water levels depending on the geometry,
392 bathymetry, and armoring in the system (e.g. Holleman and Stacey 2014). Although, even in
393 some of the POEs (e.g., Agua Hedionda) inlet accretion occurs over longer time scales and could
394 eventually transition to a more similar response to IOEs. In IOE systems, the subtidal water level
395 response to increased sea-levels will likely be stronger; however, more unknowns particularly
396 with regard to sill accretion, marsh response, and changes in tidal prism will require Climate
397 Action Plans to account for an array of possible futures. As these IOE systems are generally
398 more natural, the ecological consequences of increased water levels may be greater. Climate
399 Action Plans must weigh the tradeoffs between allowing for extreme water levels and more

400 frequent closures and the cost and impacts of management and dredging. The plans will also
401 need to be adaptable to evolving predictions and interannual variability. For example, if water
402 levels increase and there is a decrease in large wave events it is possible that an increased tidal
403 prism would lead to less frequent closures. Additionally, inlet maintenance permitting agencies
404 should allow for estuary managers to recognize that elevated sill height and large forecasted
405 waves may lead to an inlet closure and provide more permitting options that enable managers to
406 use this knowledge to schedule maintenance and dredging activity in advance.

407 **6 Summary**

408 Anomalous conditions associated with the 2015-2016 El Niño including elevated offshore water
409 levels, high waves, and low precipitation, provided the opportunity to understand how small
410 LIEs respond to oceanic forcing and insights into how they might respond to changing ocean
411 conditions. From October 2015 to May 2016, water levels were continuously measured in 13
412 estuaries in Southern California providing a unique dataset; the first time (to the authors'
413 knowledge) water levels from such a wide range of systems in the area were measured
414 simultaneously. Of the 13 systems measured, 6 were IOEs and 7 were POEs. Generally, the
415 water levels in the POEs (tidal and subtidal) were more closely correlated with offshore water
416 levels. IOE water levels responded more non-linearly to elevated offshore water levels with
417 amplified estuarine water levels. While estuary-specific dynamics and human modifications
418 complicated comparisons across estuaries, our analyses suggest that large wave heights were one
419 of the most important factors driving the IOE response which appears closely linked to changes
420 in mouth morphology, specifically sill accretion.

421 **Tables**

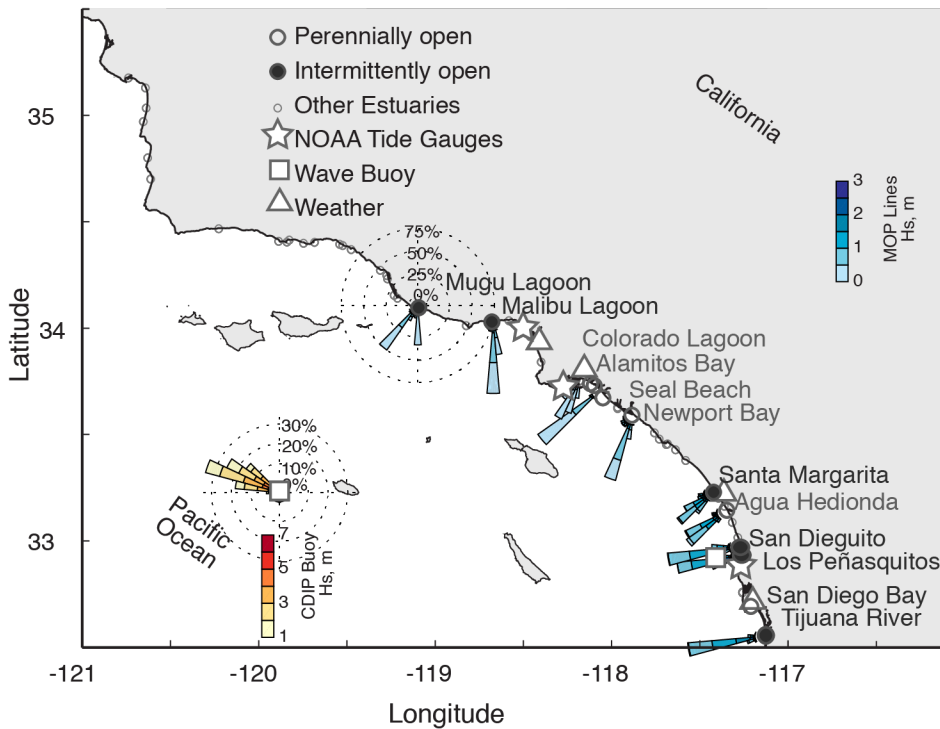
422 Table 1: Estuary inlet and water level (WL) summary statistics. Infrastructure at mouth, variance
 423 in low-passed water levels, standard deviation of low passed water level, average low-passed
 424 water level elevation, r^2 and root-mean-squared error (RSME) values for measured estuaries
 425 water level vs. measured offshore water level (at nearest tide gauge) for all estuaries, and for the
 426 open-only state for IOEs that closed during this observational period. Bold indicates an IOE.

Estuary	Mouth State	Distance Upstream of Mouth	Estuary Size, acres	Subtidal Estuary WL		Estuary WL vs. Offshore WL			
				WL Variance	Average WL Elevation	r^2	RSME	r^2_{Open}	RSME _{Open}
Mugu	Unarmoured	900 m	2050	0.006 m²	1.22 m	0.68	0.19	~	~
Malibu	Unarmoured	450 m	36	0.12 m²	1.94 m	-3.41	1.06	0.71	0.26
Los Cerritos	Jetty	4310 m	108	0.006 m ²	0.81 m	0.99	0.06	~	~
Colorado Lagoon	Jetty	4700 m	14	0.006 m ²	0.95 m	0.86	0.19	~	~
Alamitos Bay	Jetty	4300 m	583	0.010 m ²	0.87 m	0.94	0.13	~	~
Seal Beach	Jetty	3300 m	1004	0.005 m ²	1.01 m	1.00	0.03	~	~
Newport Back Bay (NB)	Jetty	6000 m	1619	0.008 m ²	0.91 m	.99	0.04	~	~
Santa Margarita Lagoon	Unarmoured	1100 m	287	0.062 m²	1.47 m	-1.77	0.83	-0.73	0.66
Agua Hedionda	Jetty	750 m	347	0.003 m ²	0.88 m	0.81	0.20	~	~
San Dieguito	Unarmoured	750 m	138	0.013 m²	1.09 m	0.26	0.42	~	~
Los Peñasquitos (LPL)	Unarmoured	750 m	238	0.119 m²	1.44 m	-1.63	0.80	0.04	0.50
San Diego Bay (SDB)	Jetty	9900m	14951	.008 m ²	0.83 m	0.99	.06	~	~
Tijuana	Unarmoured	900 m	554	0.011 m²	1.11m	0.33	0.40	0.35	0.40

Estuary									
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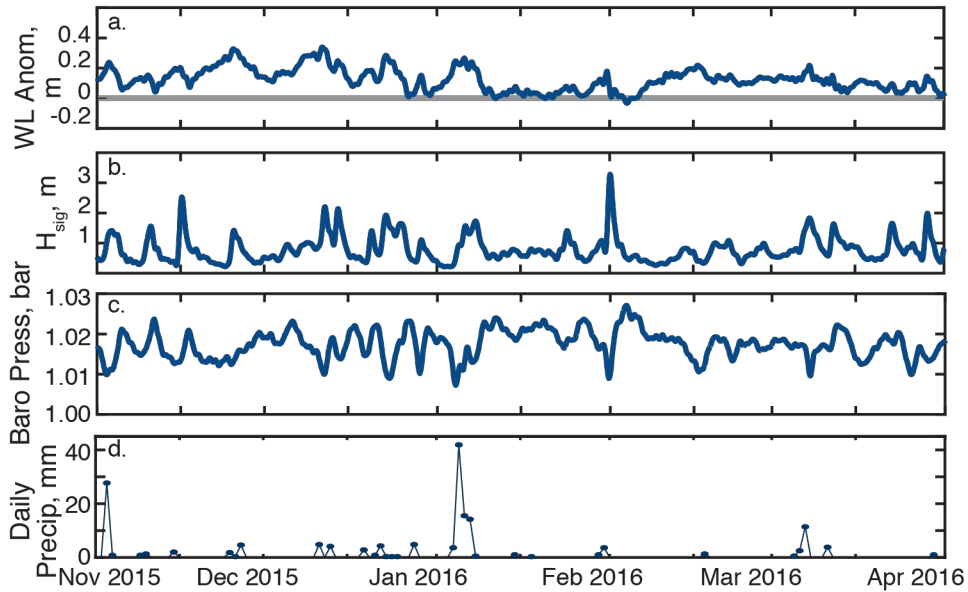
427

428 7 **Figures**



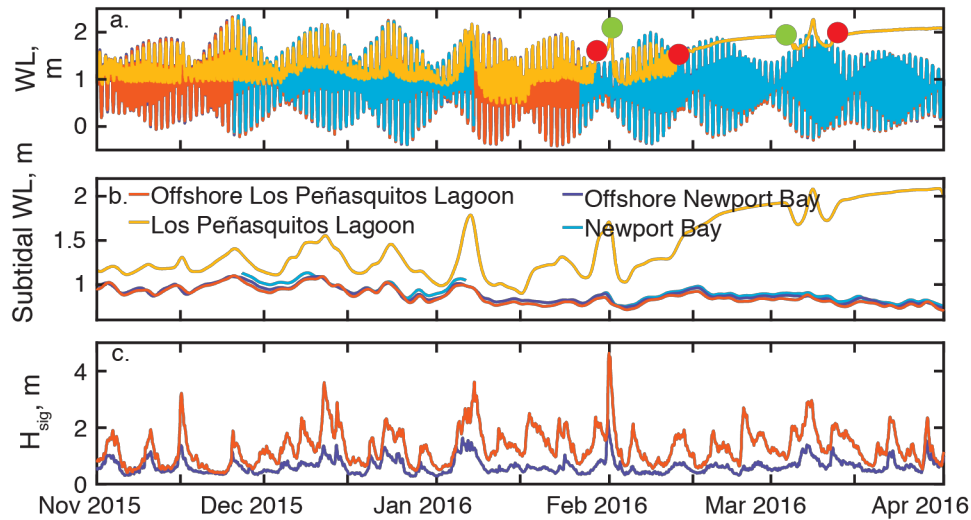
429

430 **Fig. 1** Observation Locations. Southern California coastline with estuaries (circles), tide gauges
 431 (stars), weather stations (triangles), wave buoys (squares). Estuaries included in this study are
 432 labeled and split into perennially open (large open circles) and intermittently open (large filled
 433 circles). Wave roses at each estuary entrance (blues) and offshore (oranges). Estuary entrance
 434 wave directions and significant wave height are from MOP hindcast data (cdip.ucsd.edu
 435 [O'Reilly *et al.*, 2016]). Offshore data from CDIP San Nicholas Island observational buoy
 436 (cdip.ucsd.edu). Colors indicate percent occurrence for each station of waves from Nov 01 2015
 437 to April 01 2016 within each wave height and direction band.



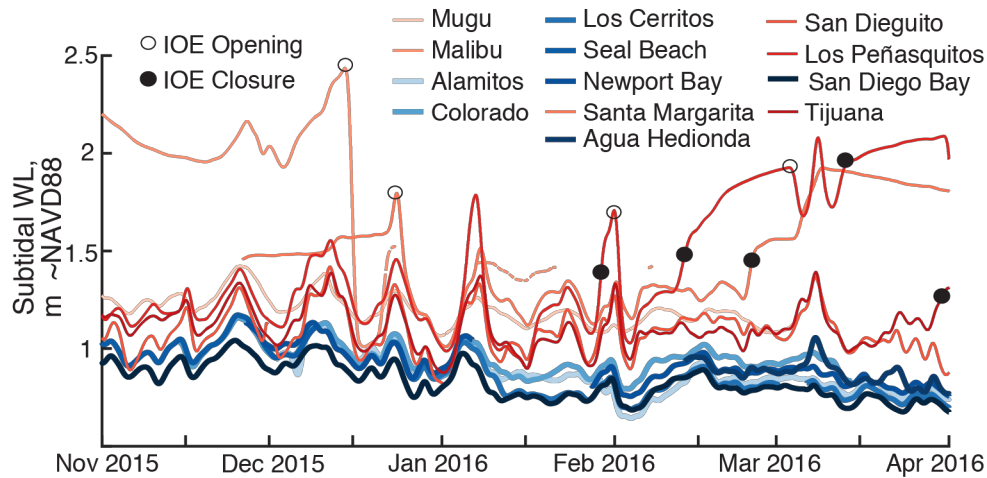
438

439 **Fig. 2** Southern California Bight Conditions a.) 24 hour low-pass water level anomaly (observed
 440 minus predicted) at La Jolla Tide Gauge [*tidesandcurrents.noaa.gov* Station ID: 9410230]. b.) 24
 441 hour low-pass filtered significant wave height from MOP hindcast line closest tide gauge.
 442 [*cdip.ucsd.edu* Station ID: D0589 c.) 24 hour low-pass barometric pressure at tide gauges d.)
 443 Daily precipitation from San Diego Airport [*ncdc.noaa.gov* Station ID: USW0023188].

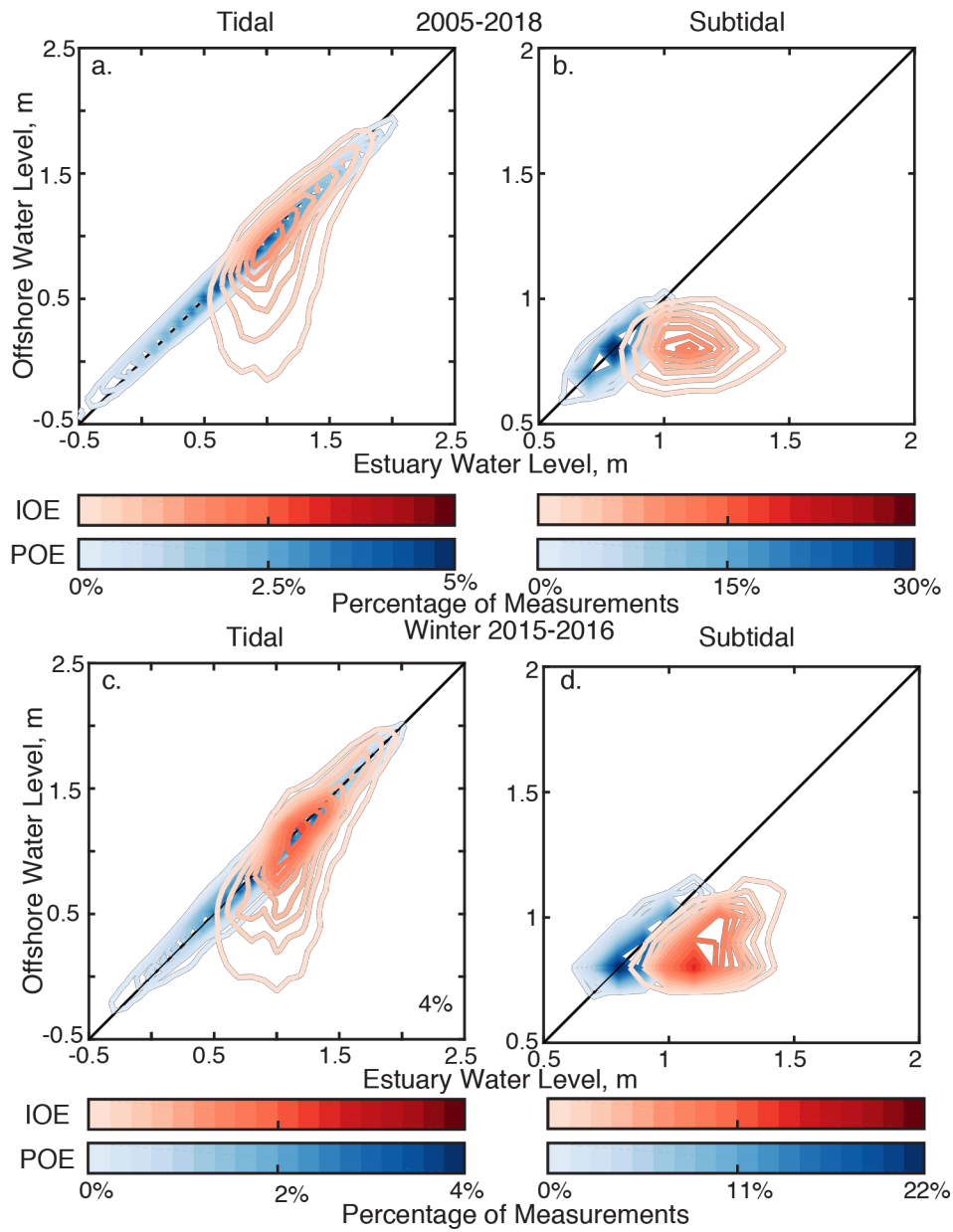


444

445 **Fig. 3** Water Levels and Offshore Waves a.) Water level measured inside (lighter) and offshore
 446 at nearest offshore sensor (darker) at Los Peñasquitos Lagoon (orange) and Newport Bay (blue)
 447 Dots indicate mouth state changes to closed (red) or open (green) b.) Subtidal (Godin filtered)
 448 water levels inside estuaries and offshore c.) MOP hindcast of significant wave height at closest
 449 line to the estuary mouth.



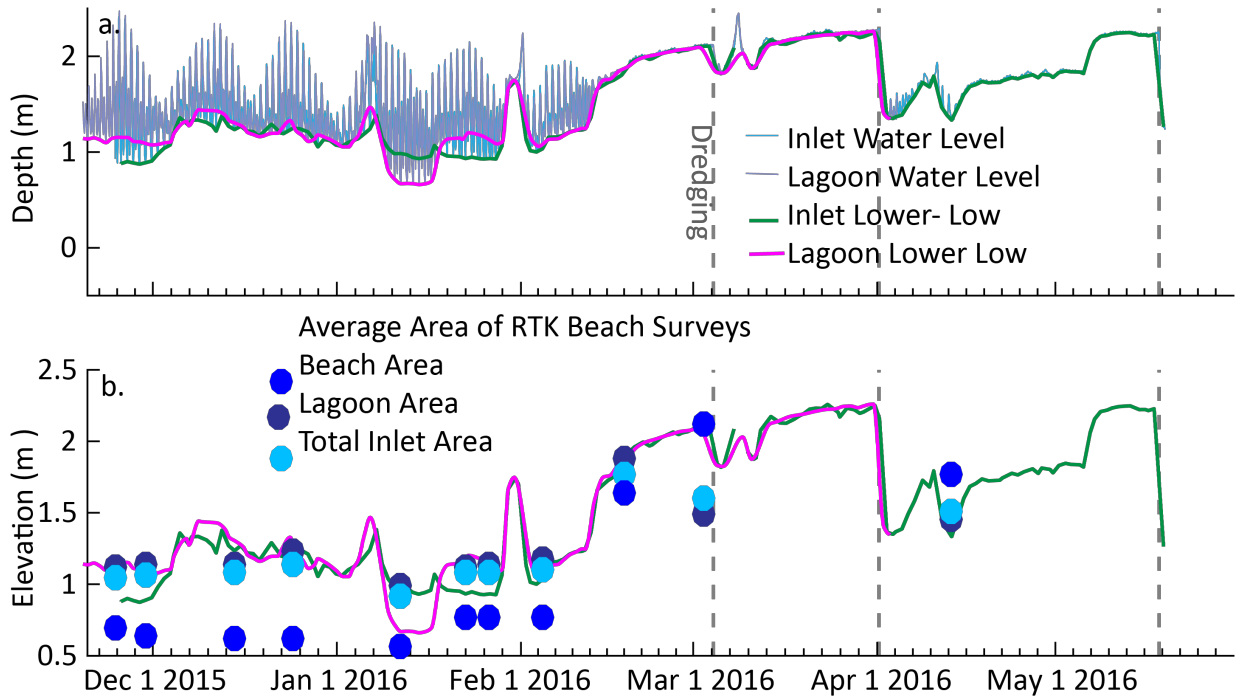
450
 451 **Fig. 4** Subtidal estuary water levels. Low-pass (Godin filtered) water levels during the
 452 observational period. Water levels from 6 estuaries were referenced to NAVD88, while those for
 453 the remaining 7 were approximately adjusted to NAVD88 by creating a best fit between the
 454 offshore higher-high tides and the estuary higher high tides during open inlet state as described
 455 in the text. Red, thin lines indicate intermittently open estuaries (IOEs) while blue, thick lines
 456 indicate perennially open systems (POEs). Estuaries are colored from North (lightest) to South
 457 (darkest). Dots indicate mouth state changes to closed (filled) or open (opened).



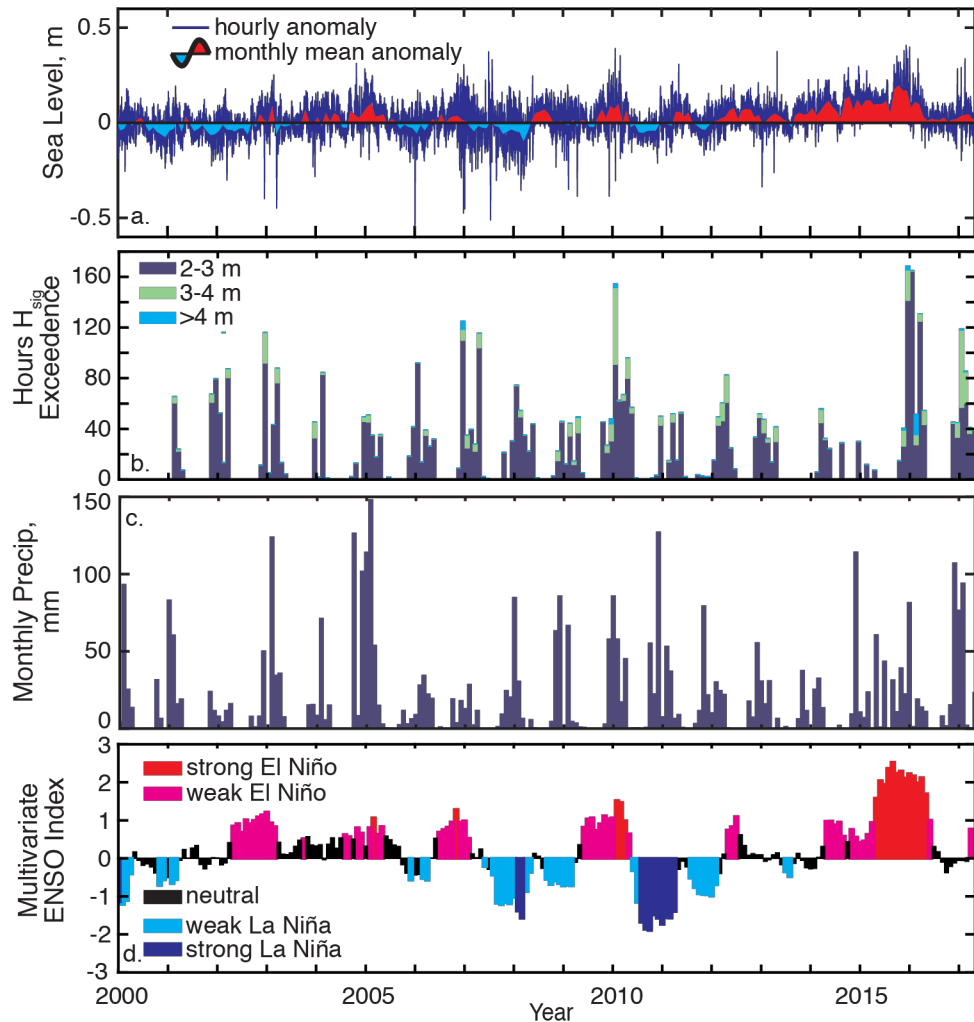
458

459 **Fig. 5** 2-Dimensional histograms of water levels a.) Instantaneous offshore water level versus
 460 estuary water level and b.) Subtidal offshore water level versus estuary water level in the IOEs
 461 (red) and POEs (blue). Colorbar and contours indicate the percentage occurrences at each water
 462 level for all IOE and POE data during open periods.

463



466 **Fig. 9** a.) Tidal water level of the Los Peñasquitos Lagoon (green) and lower-low water level
 467 (dark green) with large precipitation (light blue) and dredging events (gray) marked with vertical
 468 lines. Dots indicate mouth state changes to closed (red) or open (green) b.) Lower-low water
 469 level (as in a.) and average elevation from RTK Survey areas (as noted in Sup Figure 3.) of
 470 beach (light blue), estuary (dark blue). This comparison suggests that lower-low water is a good
 471 approximation of sill height (RMSE = .19 m).



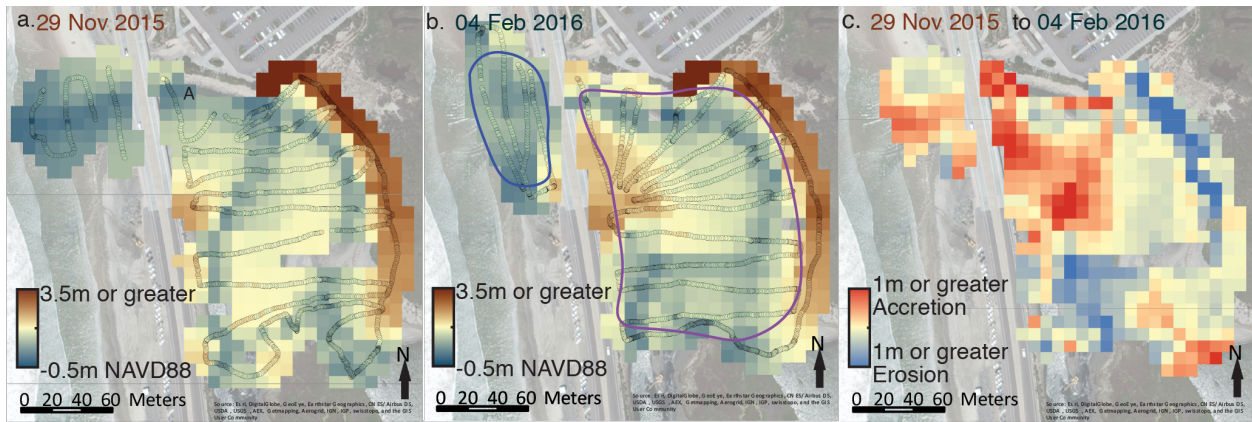
472

473 **S. 1** Conditions in Southern California Jan 2000 to May 2017 a.) Hourly and monthly mean sea-
 474 level anomaly (deviation from predicted water level) at the La Jolla tide gauge
 475 (tidesandcurrents.noaa.gov). b.) Precipitation totals from the San Diego Airport (ncdc.noaa.gov)
 476 c.) Hours when the cumulative wave height exceeded 2 (purple), 3 (green), and 4 (blue) meters at
 477 Torrey Pines Outer Buoy (cdip.ucsd.edu) d.) Multivariate Enso Index where red indicates El
 478 Niño conditions and blue indicates La Nina conditions (www.esrl.noaa.gov).

479

480 **S. 2 : Bar Graphs**

481



482

483 **SF. 3** Los Peñasquitos Lagoon topo-bathymetry. a-b) LPL inlet topography and bathymetry on
484 29 Nov 2015 (a) and 4 Feb 2016 (b). Circles indicate measurement locations. Data is gridded
485 into 8-meter grid cells using inverse difference weighted interpolation. c.) Difference between
486 gridded data set where red is deposition (accretion) and blue is erosion. The erosion seen along
487 the right of the image is the erosion of a man-made dune. The erosion at the bottom of the figure
488 is due to channel migration. Regions averaged to assess the sill height shown on Figure 8 are
489 outlined in b (purple is estuary area, blue is beach area)

490

491

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510 in this publication is for descriptive purposes only and does not imply endorsement by the U.S.
511 government.

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