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

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1 Abstract

The 2015-2016 El Niño provided insight into how estuaries in Southern California might respond to future conditions, including high offshore ocean temperatures, sea-levels, and wave heights. Low rainfall totals during the 2015-2016 winter provided the opportunity to examine how extreme ocean forcing impacts estuaries independently from fluvial events. From October 2015 to May 2016, water levels were continuously measured in 13 estuaries in Southern California. The observed systems included both intermittently and perennially open estuaries with varying watershed size, urban development, and management practices. Elevated water levels offshore (due to the combined effects of surge, tides, wave setup, and higher sea-levels) caused raised water levels and prolonged inundation in all of the estuaries studied. Water levels inside perennially open estuaries mirrored offshore water levels, while water levels inside intermittently open estuaries (IOEs) were nonlinearly elevated beyond the heightened offshore water levels. Several of the IOEs closed when sand (driven into the inlet by wave-induced sediment transport) accreted forming a barrier berm at the mouth. Closures were more persistent and occurred in more estuaries than a typical year due to the elevated water levels and large wave events. Understanding how coastal estuaries respond to increased sea-levels and the factors that predict closures in specific estuaries will help managers, scientists, and agencies develop and implement adaptation strategies.

2 Introduction

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

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

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

As communities and coastal managers develop Climate Action Plans and restoration programs (e.g., San Elijo Lagoon Conservancy AECOM 2016; Los Peñasquitos Lagoon Foundation et al. 2017), there remain several critical questions as to how these systems will respond to rising sea-levels and a changing climate, including if marsh accretion rates will keep pace with sea-level and how elevation and formation of barrier berms will change. Recent work has begun to answer these questions (Thorne et al. 2018; Doughty et al. in press), but a key unresolved issue is whether IOE closures will become more prevalent in the future and what management implications that may have.

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

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

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

3 Methods

3.1 Summary of estuaries studied

In this study, measurements were conducted in 13 estuaries (Figure 1) of varying mouth morphology, size, marsh cover, and wave exposure along the Southern California Bight. Of these systems, six estuaries are classified as intermittently open (IOE) or bar-built estuaries: Mugu Lagoon, Malibu Lagoon, Santa Margarita Estuary, San Dieguito Lagoon, Los Peñasquitos Lagoon (LPL), and Tijuana River Estuary (TRE). Seven systems are perennially open (POE) due to mouth management including dredging and/or stabilization: Colorado Lagoon, Los Cerritos, Alamitos Bay, Seal Beach, Newport Bay (NB), Agua Hedionda, and San Diego Bay (SDB). In our definition of IOE versus POE, it is important to note that most of the estuaries included here would have been IOEs under pre-development; thus here we refer to POEs as estuaries whose mouths have been structurally altered (jetties, groins, revetments, etc.) to be perennially open. The estuaries in this study are relatively small systems (14-2,050 acres, Table 1) with the exception of San Diego Bay (~15,000 acres). Generally, IOEs have a higher percentage of marsh cover than POEs (Appendix A). Some systems that straddle these definitions include ones such as the San Dieguito Lagoon where some engineering as well as maintenance dredging ensures the estuary is open, yet it still experiences significant morphological alterations near its mouth during a season and is at risk for closure. Here, because of its large morphological changes at the mouth and clear influence of the sill, we include San Dieguito Lagoon with the IOEs.

3.2 Data Collection Techniques

3.2.1 Water Level Data

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

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

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

3.2.2 Wave Data

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

3.2.3 Atmospheric Data

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

3.2.4 Berm Heights

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

4 Results

4.1 Offshore Conditions During 2015-2016 El Niño

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

The maximum offshore subtidal water levels during the study period occurred during extreme wave events and were 0.31 m, 0.30 m, and 0.31 m above the NOAA predicted subtidal water levels for La Jolla, Los Angeles, and Santa Monica respectively (Figure 2a). High subtidal water levels were due to a combination of atmospheric forcing, storm surge, and large waves events. Winter coastal water levels were correlated with both the Godin filtered significant wave heights (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, -0.73 with -0.0, -0.2, -0.2 day lag). The high correlation with barometric pressure is likely due to a combination of the effects of storm surge, waves, and changes to local offshore winds and currents caused by local storms.

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

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

4.2 Estuary water levels

Representative POEs: San Diego Bay and Newport Bay

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

Representative IOEs: Tijuana River Estuary and Los Peñasquitos Lagoon

In both TRE and LPL, sills comprised of sand and cobbles grew over the 2015-2016 winter and restricted flow or closed the respective inlets for brief periods of time (discussed further in Sections 4.3 and 4.4). During the open states, hydraulic control at the sills contribute to elongated and truncated ebbs (example from LPL shown in Figure 3a, yellow line relative to orange). The sills resulted in reduced tidal ranges (1.55 m and 1.37 m, for TRE and LPL respectively) compared with offshore ranges and contributed to low correlations between offshore and estuarine water levels (r^2 values < .4, Table 1). As a result of the lower-low tide truncation and perching, subtidal water levels in TRE and LPL (LPL is yellow in Figure 3b) were higher than offshore water levels. The LPL and TRE subtidal water levels exhibited a non-linear and amplified response to high offshore water levels (i.e., for a given offshore water level, estuarine water levels were higher, see Figure 5) for tidal and subtidal water levels, a trend consistent in a historical analysis (2005-2018, see Figure 5). Using the historical record (2005 – 2018), while analysis of water levels compared with wave energy was complicated by several factors including river flow, sill height, and importantly, dredging, elevated water levels in LPL and TRE were more frequently observed during years with larger waves when comparing the effects of large waves and offshore water levels (Sup Figure 2).

Comparison of Water levels in IOEs and POEs

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

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

4.3 Estuary Closures

During complete inlet closures, water levels increased because the sill blocked outflows while inflows from freshwater upstream continued (see for example LPL in Figure 3 and other IOEs in Figure 4). In addition, in some circumstances, large wave overtopping contributed to increased water levels behind the sill which we can deduce from time-lapse imagery and high frequency pressure measurements. During the observation period, Malibu Lagoon was closed for 30 days and naturally reopened; LPL was closed for 36 days, naturally reopened once and was mechanically breached three times; TRE was closed for 13 days (starting at the end of the study period) and was mechanically breached; Santa Margarita Estuary was closed for 44 days and naturally reopened.

4.4 Sill Height Changes over Time in Los Peñasquitos Lagoon

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

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

5 Discussion

5.1 El Niño and Implications to Future Conditions

During the 2015-2016 El Niño, elevated offshore water levels (Figure 2a) and low precipitation (Figure 2c) provided the opportunity to understand how small LIEs respond to oceanic forcing. The sea-level anomaly associated with the 2015-2016 El Niño in La Jolla is comparable to the amount of sea-level rise likely to occur by 2030 (Griggs et al, 2017), with some estimates of much higher rates of sea-level rise possible (e.g., Sweet et al. 2017). As described in more detail in Young et al. 2018, although modeling suggests that storm tracks are projected to shift pole-ward resulting in decreased waves in the Southern California Bight (i.e. Erikson et al. 2016, Graham et al., 2013) there is nonetheless likely to be an increase in extreme water levels due to rising seas alone in Southern California (Tebaldi et al. 2012; Sweet and Park, 2014). Additionally, while difficult to predict, there is some suggestion of more frequent El Niño events (Cai et al. 2014) with a changing climate. Therefore, these estuaries will experience more extreme water level events in the future and possibly more frequent El Niño conditions.

5.2 Morphodynamics in IOEs

Significant morphological changes near the mouth were observed in most of the IOEs during the observation period (as evident from increasing lower-low water levels and time-lapse imagery). The enhanced sill accretions and more frequent and persistent closures observed in IOEs in Southern California during the 2015-2016 El Niño season (as presented here and from a different dataset in Young et al. 2018 which built off Elwany et al. 1998) can be attributed to the anomalously large wave conditions coupled with anomalously low precipitation, as expected from the Behrens et al. (2013) model of inlet accretion. In both LPL and TRE, multi-year water level records indicate that sill heights generally increased during large wave events and decreased during significant flushing events. Additionally, years with larger wave events were years with higher estuarine water levels, higher sills, and more closure days (Supplementary Material, 2). Unfortunately, sparse data and periodic dredging precluded further analysis. In the four southern IOEs, the sill heights grew during the largest wave events during this study.

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

5.3 Comparison of IOEs and POEs

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

Decoupling the effects of marsh extent and mouth morphology with this limited dataset is challenging because in Southern California, IOEs are generally more natural systems with higher percentages of marsh while POEs are more heavily managed and channelized (Appendix A). The overall trends seen in Figure 6 are consistent with the hypothesis that the percentage of marsh extent impacts water levels inside of these estuaries (with more marsh leading to higher water levels). However, in a direct comparison between estuaries with similar percentages of marsh habitat (Appendix A), it appears that mouth morphology (i.e., the presence/absence and size of a sill) plays a more important role in setting the mean estuarine water levels.

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

5.4 Southern California Estuary Management Implications

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

If closures become more frequent under future conditions as they did during the El Niño, the estuaries would be subjected to more inundation of freshwater on saline or brackish habitats, more frequent hypoxic conditions, longer periods of inundation at a fixed elevation, and pose a greater risk for upstream flooding. For example, it has been observed that more frequent inlet closures cause a shift from more saline marsh vegetation to more freshwater vegetation as the surface layer over the marsh is fairly fresh (Los Peñasquitos Lagoon Foundation 2017). Additionally, reduced tidal prism would cause physiologically stressful conditions and a reduction of incoming marine propagules leading to changes in species composition and an overall reduction in diversity of plants and animals (Teske and Wooldridge 2001; Phlips et al. 2002; Raposa 2002; Saad et al. 2002). During the 2015-2016 El Niño, mouth closures in TRE and LPL resulted in hypoxia and subsequent fish kills within days. Similarly, sustained high water in NB resulted in die-off of high marsh habitat that has been used as past nesting habitat for several sensitive bird species (Dick Zembal, personal observations). The risk for upstream flooding and inundation - including nearby infrastructure - increases during closures as the estuaries slowly fill with upstream incoming fresh water and wave overtopping.

LIEs in Southern California (and around the world) are all managed by different entities with varying priorities, stakeholders, and economic and ecological values (e.g. Pratt 2014; Zedler and Kercher 2005). As different management entities develop Climate Action Plans for their respective systems, they must take sea-level rise into account. This study demonstrates that water level response (and therefore appropriate management strategies) will vary by system. In more perennially open systems, near the mouth it is expected that the water levels will continue to match the water levels offshore with upstream water levels depending on the geometry, bathymetry, and armoring in the system (e.g. Holleman and Stacey 2014). Although, even in some of the POEs (e.g., Agua Hedionda) inlet accretion occurs over longer time scales and could eventually transition to a more similar response to IOEs. In IOE systems, the subtidal water level response to increased sea-levels will likely be stronger; however, more unknowns particularly with regard to sill accretion, marsh response, and changes in tidal prism will require Climate Action Plans to account for an array of possible futures. As these IOE systems are generally more natural, the ecological consequences of increased water levels may be greater. Climate Action Plans must weigh the tradeoffs between allowing for extreme water levels and more frequent closures and the cost and impacts of management and dredging. The plans will also need to be adaptable to evolving predictions and interannual variability. For example, if water levels increase and there is a decrease in large wave events it is possible that an increased tidal prism would lead to less frequent closures. Additionally, inlet maintenance permitting agencies should allow for estuary managers to recognize that elevated sill height and large forecasted waves may lead to an inlet closure and provide more permitting options that enable managers to use this knowledge to schedule maintenance and dredging activity in advance.

6 Summary

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

Tables

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

				Subtidal Estuary WL		Estuary WL vs. Offshore WL			
Estuary	Mouth State	Distance Upstream of Mouth	Estuary Size, acres	WL Variance	Average WL Elevation	r^2	RSME	r^2_{Open}	RSME $_{Open}$
Mugu	**Unarmoured**	**900 m**	2050	**0.006 m^2**	**1.22 m**	**0.68**	**0.19**	**~**	**~**
Malibu	**Unarmoured**	**450 m**	36	**0.12 m^2**	**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 m^2**	**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 m^2**	**1.09 m**	**0.26**	**0.42**	**~**	**~**
Los Peñasquitos (LPL)	**Unarmoured**	**750 m**	**238**	**0.119 m^2**	**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 m^2**	**1.11m**	**0.33**	**0.40**	**0.35**	**0.40**

Estuary									

7 Figures

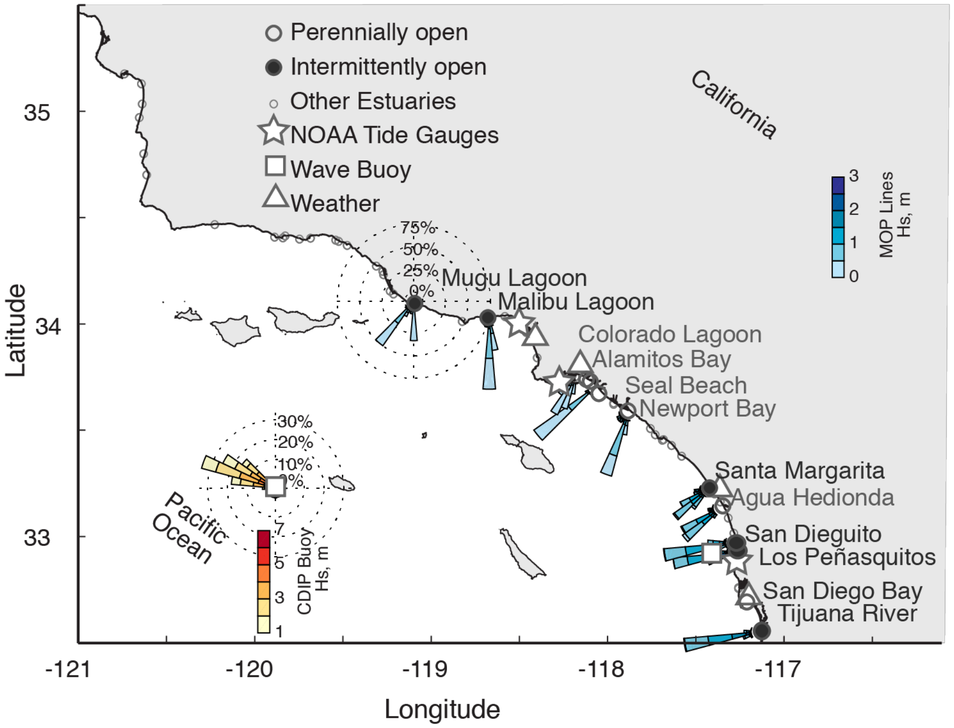


Fig. 1 Observation Locations. Southern California coastline with estuaries (circles), tide gauges (stars), weather stations (triangles), wave buoys (squares). Estuaries included in this study are labeled and split into perennially open (large open circles) and intermittently open (large filled circles).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

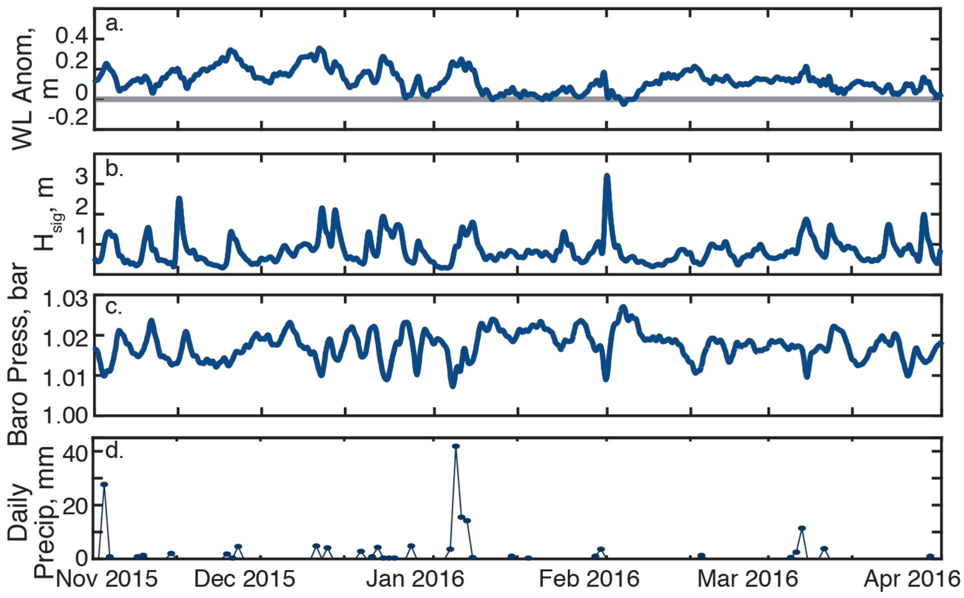


Fig. 2 Southern California Bight Conditions a.) 24 hour low-pass water level anomaly (observed minus predicted) at La Jolla Tide Gauge [*tidesandcurrents.noaa.gov* Station ID: 9410230]. b.) 24 hour low-pass filtered significant wave height from MOP hindcast line closest tide gauge. [*cdip.ucsd.edu* Station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

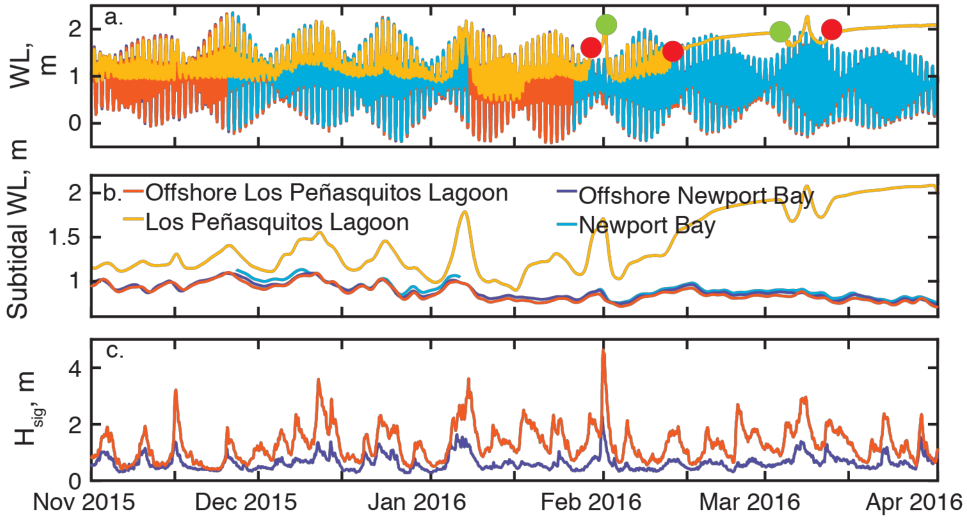


Fig. 3 Water Levels and Offshore Waves a.) Water level measured inside (lighter) and offshore at nearest offshore sensor (darker) at Los Peñasquitos Lagoon (orange) and Newport Bay (blue) Dots indicate mouth state changes to closed (red) or open (green) b.) Subtidal (Godin filtered) water levels inside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

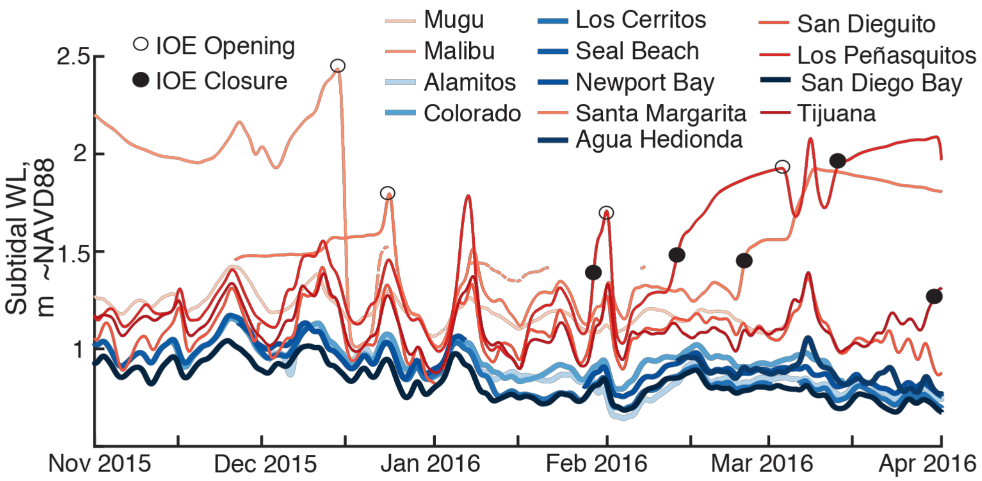


Fig. 4 Subtidal estuary water levels. Low-pass (Godin filtered) water levels during the observational period. Water levels from 6 estuaries were referenced to NAVD88, while those for the remaining 7 were approximately adjusted to NAVD88 by creating a best fit between the offshore higher-high tides and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

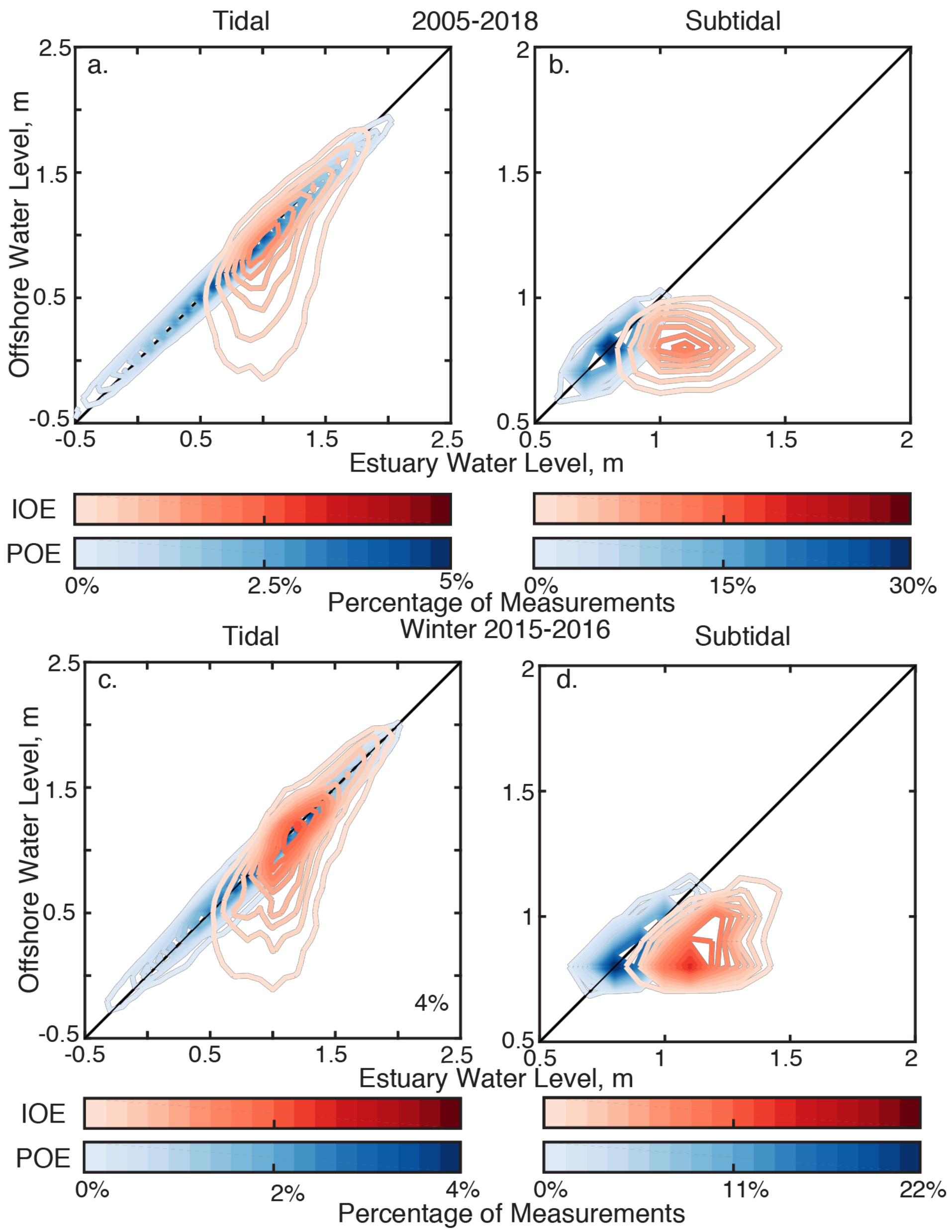


Fig. 5 2-Dimensional histograms of water levels a.) Instantaneous offshore water level versus estuary water level and b.) Subtidal offshore water level versus estuary water level in the IOEs (red) and POEs (blue). Colorbar and contours indicate the percentage occurrences at each water level for all IOE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

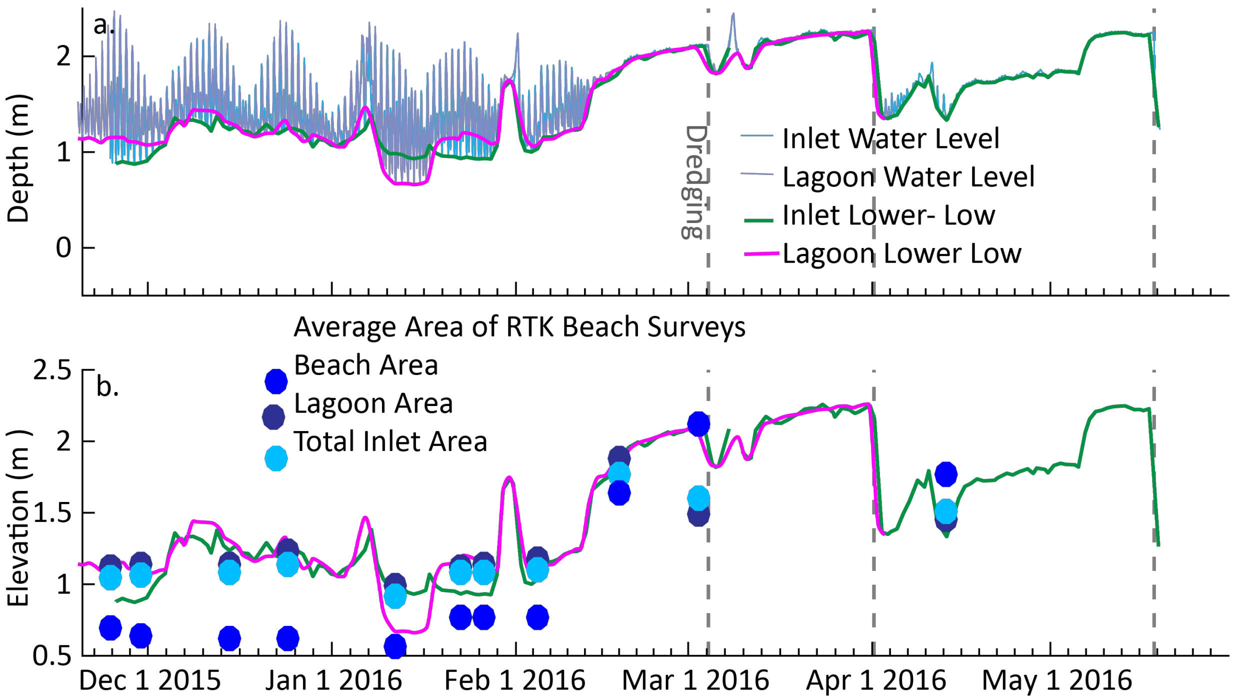
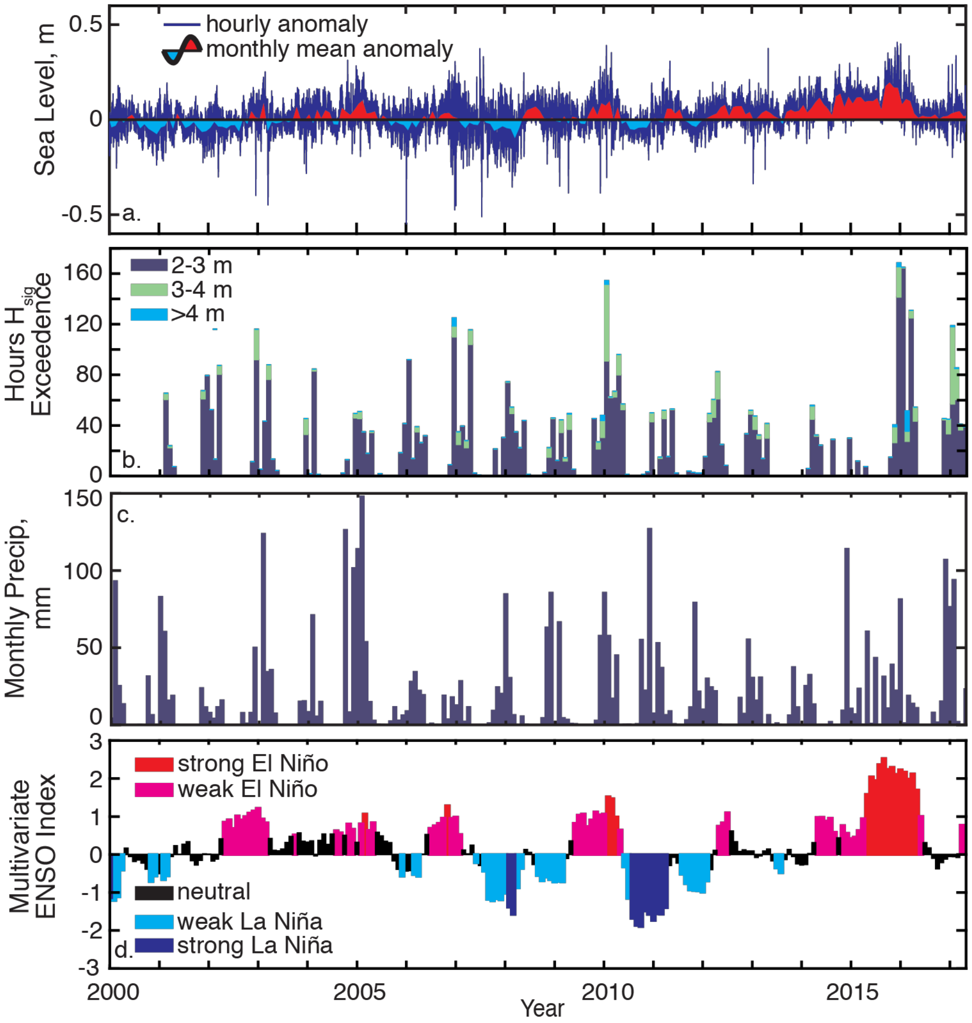
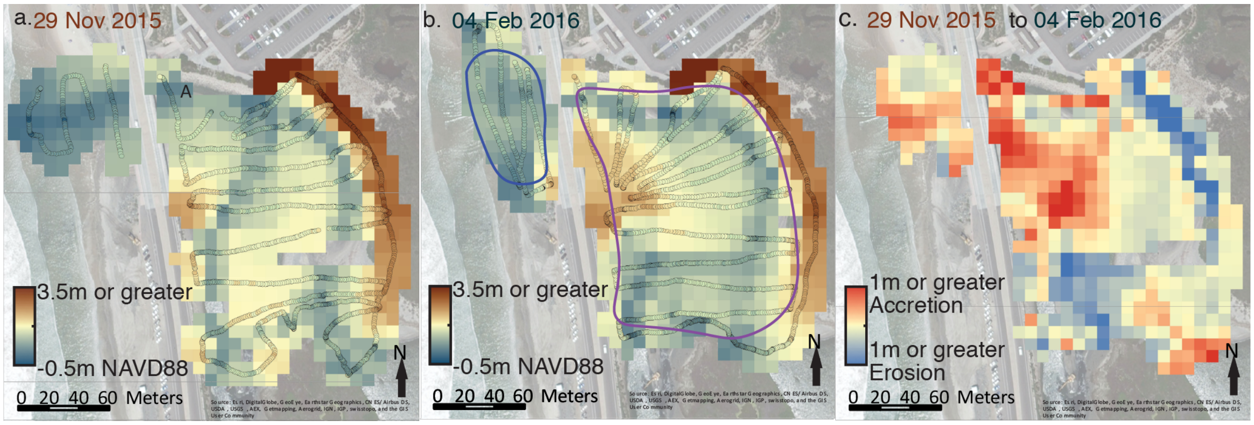


Fig. 9 a.) Tidal water level of the Los Peñasquitos Lagoon (green) and lower-low water level (dark green) with large precipitation (light blue) and dredging events (gray) marked with vertical lines. Dots indicate mouth state changes to closed (red) or open (green) b.) Lower-low water level (as in a.)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



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

S. 2 : Bar Graphs



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

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