Title

Shifting Sands: Using a Sediment Budget Model to Predict Beach Width Changes for Cardiff State Beach

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SHIFTING SANDS: USING A SEDIMENT BUDGET MODEL TO PREDICT BEACH WIDTH CHANGES FOR CARDIFF STATE BEACH

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1. Executive Summary

Cardiff State Beach (CSB) in Encinitas, CA is a barrier bar, sandy beach in San Diego County along the west side of the San Elijo Lagoon. The beach has been nourished by sand placement several times over the past twenty years to enhance its width amidst erosive wave events. In addition, San Elijo Lagoon "bypassing" (dredging of sand from the inlet) has been routinely conducted and the resulting sand placed on the beach. CSB is also the location for a Living Shoreline project that built a vegetated dune system along the western edge of South Coast Highway 101. In the interplay between rising sea levels, changing wave climate and human management efforts, projecting beach width would enable an understanding of coastal sediment management practices needed to maintain beach width ("hold the line"). The objective of this capstone project was to use a sediment budget model created for Cardiff beach to project change in beach width for 2022-2050, assuming two strong El Nino winters and sea level rise scenarios outlined by the NOAA sea level rise technical report (2022). The model was then validated using a hindcast and then comparing to existing datasets from SIO and SANDAG surveys for the 2000-2020 period. Our preliminary results indicate a promising scenario of beach width increase for CSB during the period considered, even just with routine yearly bypassing. However, in the absence of human intervention in the form of added sand, El Niños and sea level rise take a toll on the beach width, decreasing it by ~25 m by the end of the three decades. The movement of sand between the dunes and the nearshore zone is a novel element of this model that needs to be assessed further during future El Niños or other highly energetic winter wave seasons. This work is intended to support the City of Encinitas and San Diego Association of Governments' (SANDAG) beach monitoring program by providing future beach scenarios to enable decision-making around nourishment activities and coastal resilience.

2. Introduction

A beach sediment budget refers to the balance between the net sediment change over time within a defined geographic unit, often referred to as a littoral cell[1] , versus the various inflows (sources) and outflows (sinks) of sediment to that unit. Typical sediment sources include rivers, bluffs, dunes, and sand nourishment (artificial placement of sand on beaches). Sediment sinks include erosive storms (e.g., associated with El Niño Southern Oscillation or ENSO) and wind transport among others. Sediment budget information clarifies whether beaches within a littoral cell are eroding (inflow < outflow), accreting (inflow > outflow), or stable (inflow = outflow).

Cardiff State Beach (CSB) in Encinitas, CA is a barrier bar, gently sloping, sandy beach in San Diego County along the west side of the San Elijo Lagoon (Figure 1). CSB is bounded in the north by Cardiff Reef North and in the south by Seaside Reef, with an alongshore distance of 1.7 km.

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[1] List, J.H. (2005) Sediment Budget. Encyclopedia of Coastal Science. Encyclopedia of Earth Science Series, Schwartz M.L. (eds)

The San Elijo Lagoon inlet has been stabilized due to human modifications to the system. This interrupts the typical North-South flow of sand in the littoral cell, thereby filling up the inlet with sand. The sand captured in the inlet channel is dredged annually and moved to the downdrift beach (south of the inlet), referred to as "bypassing". This type of beneficial sand placement has been historically used to return sediment to the littoral system that has been trapped by coastal features such as lagoon entrances[4]. San Elijo Lagoon bypassing, combined with other entrance maintenance activities, has been conducted since 1994, leading to a routine supply of sand for the beach. An additional key feature on CSB is the Cardiff Beach Living Shoreline dunes project (dunes)[2]. The dunes, completed in May 2019, are hybrid coastal structures designed to protect the coastline while providing natural habitats, human recreation and enhancing coastal ecosystems. These dunes were constructed from material dredged from the lagoon bypassing operations during 2018 and 2019.

The beach's sediment budget is determined by sea level changes, wave climate and coastal management efforts. Sand nourishment overlaid with erosive ENSO conditions has resulted in a surplus sediment budget from 1998 to 2019, leading to a corresponding beach width increase of 25 m (accretion)[3]. The nearshore volume (source of CSB's sand supply) has increased by 200,000 m^3 since 2007[4]. Nearshore zone is defined as 1700 m alongshore stretch of beach extending out to -8 m water depth. The observed increase in nearshore volume is consistent with the amount added to the system through nourishment and bypassing for the nine-year period from 2007-2016, thereby establishing that the sand added to the system is retained in this area. As described in the beach report, nourishment and bypassing have led to an accreting beach, with an average beach width recovery rate of +4m/year between El Niños.

In the context of supply considerations of sand, potential synergies with the dunes and rising sea levels, a sediment budget projection for CSB is critical to inform future coastal management approaches. For this capstone project, change in beach width is estimated based on a sediment budget projection for 2022-2050 period, while also comparing datasets from historical San Diego Association of Government (SANDAG) surveys and Scripps Institution of Oceanography (SIO) Jumbo and LiDAR surveys for CSB. The sediment budget model covers the entire 1700 m stretch of beach and predicts the mean beach width as a proxy for net sand volume. The results of this study are intended to provide preliminary indicators of how sand supply considerations may be impacted by sea level rise and inform the collaborative efforts of the City of Encinitas and SANDAG toward effective coastal management. The underlying question is - can sand management practices "hold the line" and maintain a stable CSB given projected sea level rise combined with erosive ENSO events?

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[2] Winters, M.A.; Leslie, B.; Sloane, E.B.; Gallien, T.W. Observations and Preliminary Vulnerability Assessment of a Hybrid Dune-Based Living Shoreline. J. Mar. Sci. Eng. 2020

[3] San Diego beach report: https://siocpg.ucsd.edu/data-products/beach-report-guide/. Direct link to "Case Study: Cardiff State Beach" section: https://storymaps.arcgis.com/stories/7bf1a184d0b24589a331b7b85cdbd13f

[4] SANDAG Shoreline Monitoring Program Annual Report (2020)

Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community,
Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap

Figure 1: Cardiff State Beach
Yellow rectangle denotes the study area portion of the beach, spanning 1700 m alongshore. Pink shaded area denotes the north-south boundaries of the Cardiff Living Shoreline Dunes on the back beach along Coast Highway 101. San Elijo Lagoon is to the east, with the yellow arrow pointing to its inlet on the northern boundary of CSB. The two reefs along the beach are also shown.

3. Materials and methods

Yearly Sediment Budget Equation for Mean Shoreline Change

Based on the CSB report[3] and compiled datasets of annual beach width and sand volume changes at CSB since 2007[5], the annual change in mean beach width location $\Delta\bar{X}_{MSL}$ is conceptualized in Figure 2. The annual change in the mean beach width is assumed to be governed by 1) a change to the total sand volume of the survey area, 2) ENSO-driven multi-year cross-shore migration of sand *within* the survey area, and 3) sea level rise. Definitions of terms in the equation and their estimates are detailed in Appendix A.

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[5] Ludka, B. C., Guza, R. T., O'Reilly, W. C., Merrifield, M. A., Flick, R. E., Bak, A. S., ... & Boyd, G. (2019). Sixteen years of bathymetry and waves at San Diego beaches. *Scientific data*, *6*(1), 1-13.

$$\Delta\bar{X}_{MSL} = C_{Equil} * \underbrace{[\ V_{Bypass} + V_{Nourish} - V_{\text{ElNiño}} + V_{Dune}\ ]}_{\boxed{\text{Nearshore volume change}}} + \underbrace{[-\Delta\bar{X}_{\text{ElNiño}} + \Delta\bar{X}_{Recovery}\ ]}_{\boxed{\text{ENSO cycle retreat and recovery}}} - \underbrace{\frac{\Delta Z_{SL}}{\beta_{SL}}}_{\boxed{\text{Sea level rise (retreat)}}}$$

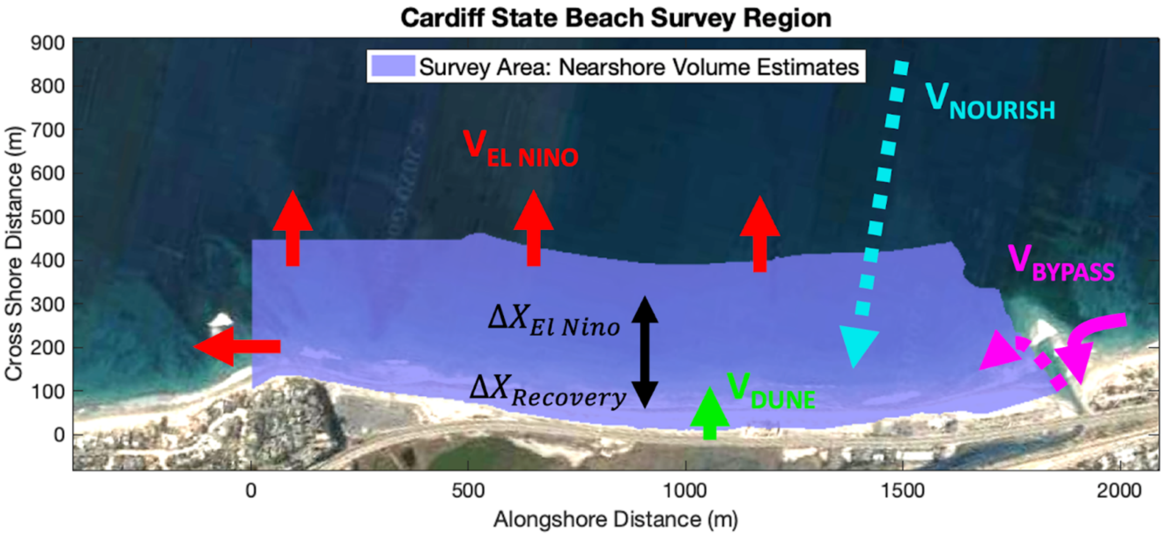

Figure 2: Sediment budget model for Cardiff State Beach
The sediment budget model (upper panel) and a schematic representation of the terms at Cardiff State Beach (lower panel). The model shows Annual change in mean beach width as a function of nearshore volume change, ENSO cycle changes and sea level rise. Lower panel: Bypassed sand, V_{Bypass}, is the added sand volume dredged from the inlet channel area. It is assumed that the sand is either from the lagoon or has migrated downcoast from San Elijo State Beach before being deposited in the inlet by tidal currents.

Sea level rise scenarios

Sea level rise scenarios are based on near-term (2020-2050) estimates from the 2022 NOAA sea level rise technical report[6]. A time series of the La Jolla sea level projections is shown in Figure 3. The sea level change term in Figure 2 for any given year was obtained by linearly interpolating between the decadal projections for Relative Sea Level at the La Jolla location in the NOAA report. For this analysis, the low (0.3 m rise by 2100), intermediate (1.0 m) and high (2.0 m) scenarios were used, with the associated 17th and 83rd percentile levels as upper and lower bounds.

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[6] Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak. Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. 2022

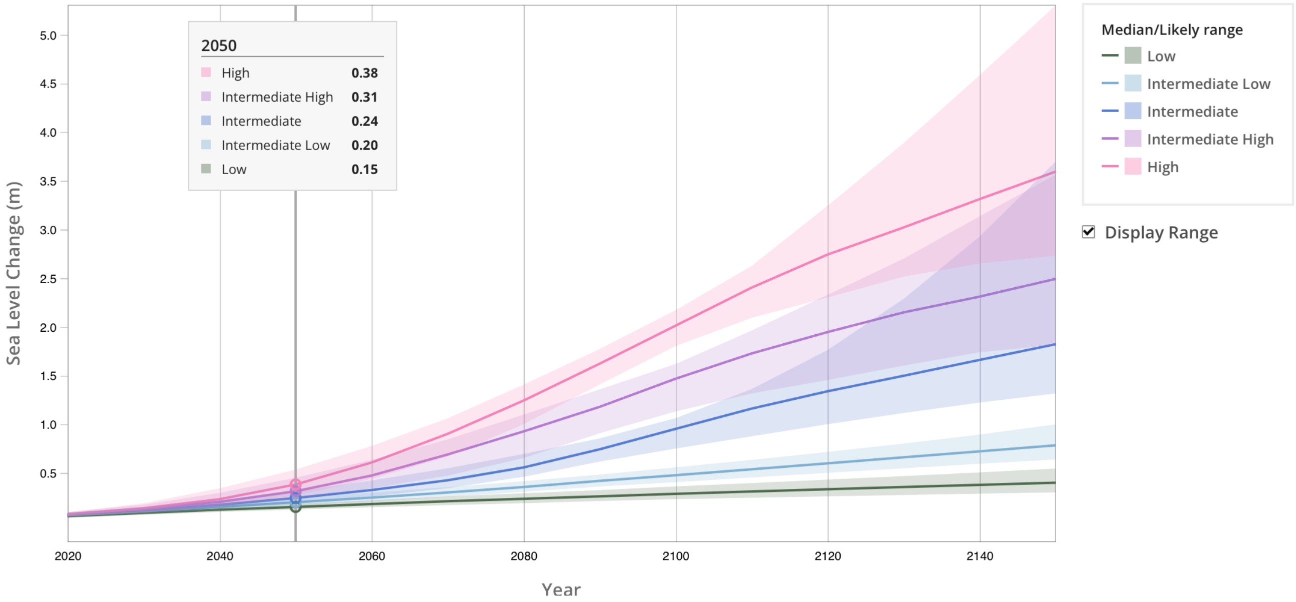

Figure 3: La Jolla sea level rise
Sea level change time series for the La Jolla (Scripps Pier) location are shown in this graph obtained from interagency sea level rise scenario tool[7]. There are five sea level scenarios: low, intermediate-low, intermediate, intermediate-high and high shown. These scenarios are defined by a target global mean sea level (GMSL) value in 2100. Median values are provided for each scenario, along with likely ranges represented by shaded regions showing the 17th-83rd percentile ranges. All values are relative to a baseline year of 2000, with median values for 2050 shown in the inset.

Projections and calculations

Beach width data for CSB were obtained from the Scripps Institution of Oceanography (SIO) San Diego Beach Report and Ludka et al[3,5], and from SANDAG (the appendices of the 2020 shoreline monitoring report prepared by Coastal Frontiers)[4]. SIO surveys of CSB consisted of truck lidar surveys (monthly, 2018-present) and ATV/ dolly/jetski surveys (quarterly, 2007-present). The study region corresponds to transects 673 to 677 in the Monitoring and Prediction System (MOP)[8]. For the SANDAG data dating back to 1980, beach width each year was obtained by averaging data from transects SD-0625 and SD-0630 taken in the Fall of the previous year and Spring of the current year. Both SIO and SANDAG beach widths were offset to obtain estimates of change in beach width estimate relative to 2000. Validation datasets are in Appendix C.

El Niño events are assumed to have two impacts on the CSB sand budget. First, the beach retreats during the El Nino year and slowly recovers each year (the $\Delta\bar{X}_{ElNi\tilde{n}o}$ and $\Delta\bar{X}_{Recovery}$ on the right-hand side of $\Delta\bar{X}_{MSL}$ equation). Second, dune erosion is assumed to occur during "strong" El Niño years. El Niño frequency is assumed to be once every seven years. In the analysis where impact of El Niño is assessed, a cadence of once every ten years is used as a comparator. These cadences are selected as representative cases based on historical

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[7] Interagency sea level rise scenario tool: https://sealevel.nasa.gov/task-force-scenario-tool?psmsl_id=256
[8] O'Reilly, W. C., Olfe, C., Thomas, J., Seymour, R. J., & Guza, R. T. (2016). The California coastal wave monitoring and prediction system. Coastal Engineering, 116, 118-132. https://doi.org/10.1016/j.coastaleng.2016.06.005

observations along the California coast[9]. Dune erosion is a source of sand for the nearshore budget (V_{Dune}). The estimation of V_{Dune} is described in Appendix B. To translate sea level rise to shoreline retreat, we used the Bruun rule[10], which provides a relationship between sea level rise and shoreline recession. It assumes that the shoreline retreat is equal to the change of sea-level divided by the slope of the upper shoreface. For this analysis, we set the mean annual shoreface slope to 0.02 (1/5) based on slope at mean shoreline (MSL) location[5]. X_{MSL} calculations were performed using Microsoft Excel® and graphed using GraphPad Prism®.

4. Model Validation

A hindcast of X_{MSL} for 2000-2020 is obtained by solving the X_{MSL} equation using forcing terms that account for actual bypass rates and three El Niño occurrences during the time span (Appendix C). Observed beach widths from the SIO and SANDAG datasets were used to validate the modeled X_{MSL}. The model is able to capture the overall positive trend in observed beach width as well as the beach narrowing, and the more gradual recovery associated with the 2015-16 El Niño (Figure 4). The hindcast does not incorporate sea level rise losses as local sea level trend is not statistically different than zero during 2000-2020 based on the La Jolla tide gauge time series[11]. Although the SANDAG beach width is based on only two transects collected twice a year, the estimate compares reasonably well with the SIO beach width, which is determined from twice as many surveys in time, with 20 transects spanning CSB. These findings provide additional confidence that our prediction algorithm can model the study area appropriately.

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[9] Smith, S.A., & Barnard, P.L. (2021) The impacts of the 2015/2016 El Niño on California's sandy beaches, Geomorphology, Volume 377

[10] Bruun, P. (1962). Sea-level rise as a cause of shore erosion. Journal of the Waterways and Harbors division, 88(1), 117-130

[11] NOAA Tides and Currents: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9410230

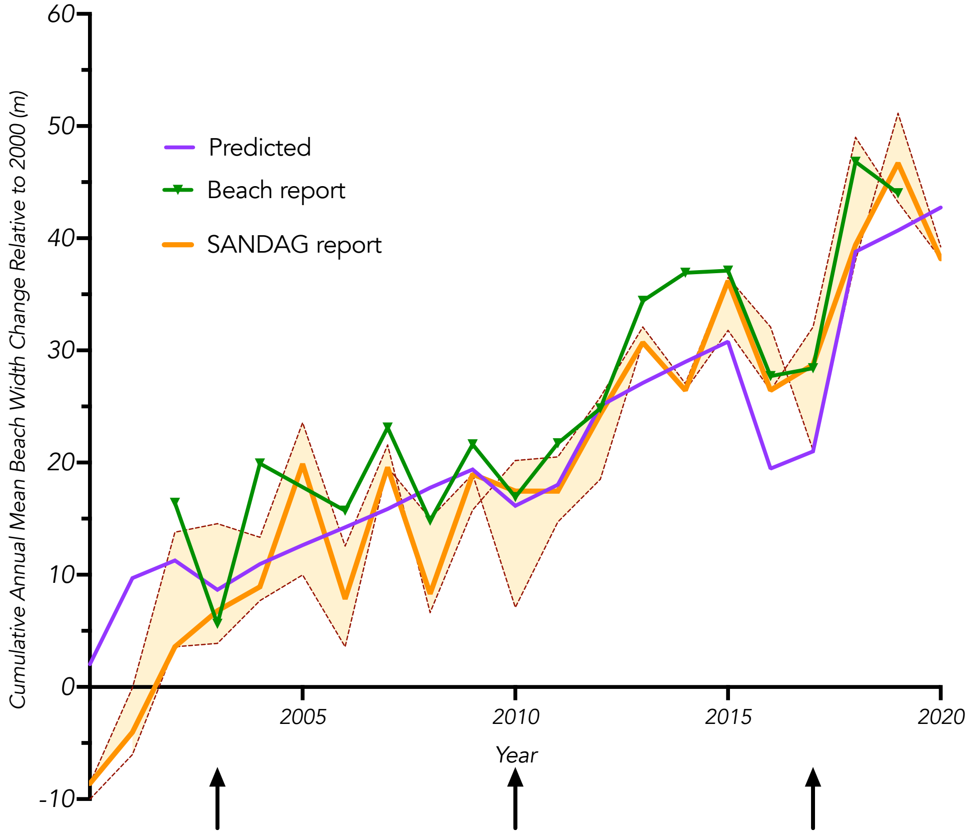

Figure 4: Model validation
Predicted vs. reported beach width comparison from 2000-2020 between SANDAG/Coastal Frontiers report, beach report and predicted datasets. A simple offset relationship is used to convert beach report and SANDAG datasets to mean beach width change. The SANDAG data are reported as a median between two transects, each measured twice a year. Shaded area represents the range between the median of two transects (SD-0630 and SD-0625). Arrows denote El Niño years (2016 was a strong El Niño year).

5. Projected Beach Change

Projections point to an accreting beach if bypass continues at current rate through 2050

The equation for X_{MSL} is used to estimate annual mean beach width change from 2020 through 2050 with three alternatives: (1) Yearly bypass, where sand bypassing from the San Elijo Lagoon inlet is assumed to be 20,000 m^3 per year through 2050, (2) half bypass, performed at a reduced rate of 10,000 m^3 per year, or (3) no bypass (completely stopped), as shown in Figure 5.

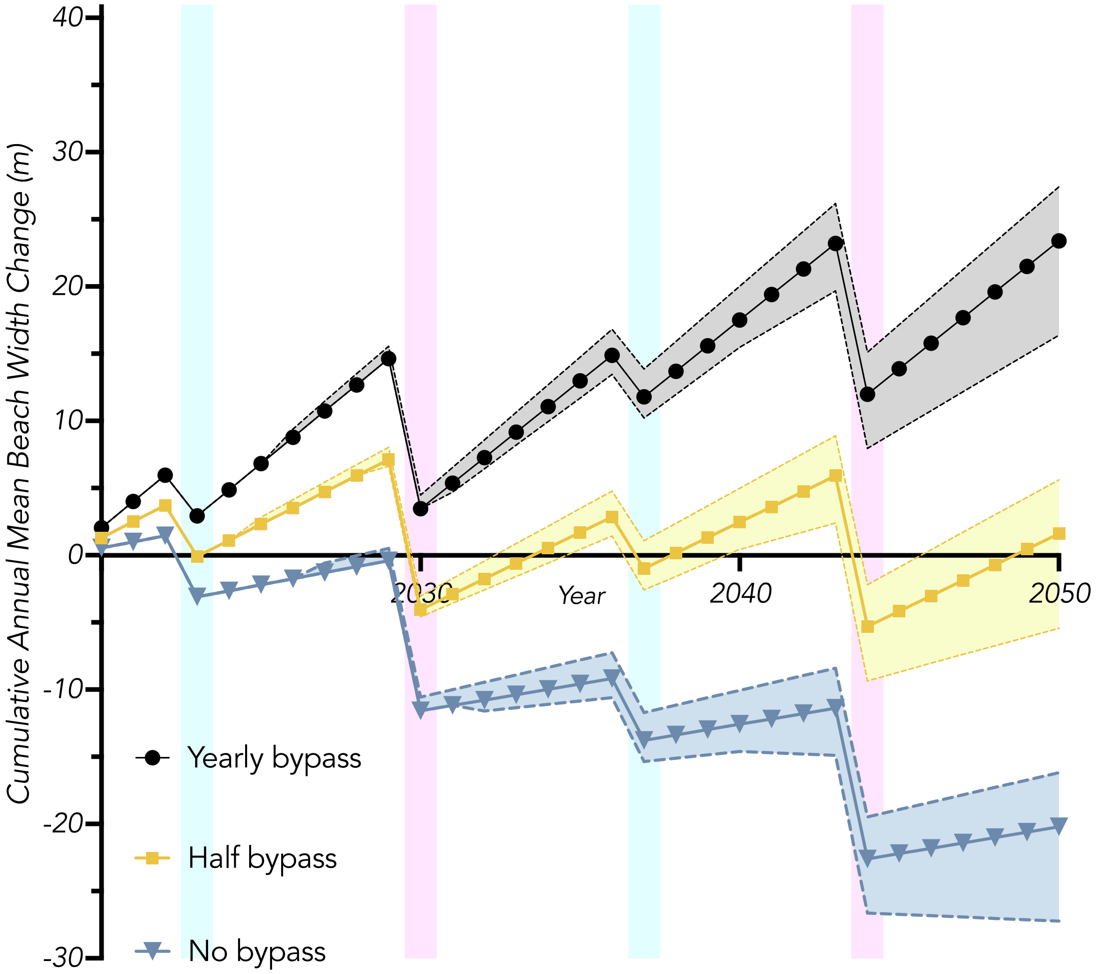

Figure 5: Projected cumulative annual mean beach width changes with yearly, half and no bypass cases. Yearly bypass vs. half-bypass are compared to the no bypass scenario. The assumption is that there is no additional nourishment performed during this period. Time series estimates with upper and lower bounds denote use of median and 17th and 83rd percentile sea level projections for low, intermediate, and high sea level rise scenarios. Pink and blue shaded areas represent El Niño years, pink being the "strong" years.

The projection for case 1 shows a trend toward an accreting beach, with the mean beach width increase of ~23.5 m in 2050 (Figure 5). The largest reductions in beach width (~11 m) are observed during both the "strong" El Niño years 2030 and 2044, in line with expectations. A "hold the line" scenario is predicted using a 10,000 m^3 bypass, wherein the average beach width stays nearly constant for this period (case 2). In this case, the annual mean beach width change cycles between +7 m and -5 m from its present width. In both cases 1 and 2, the impact of sea level rise on X_{MSL} is not trivial but quite manageable based on current (or even reduced) bypassing capabilities. However, in the no bypass scenario, a step reduction in beach width is observed with every El Niño event, and the 2050 beach width is reduced by ~20 m relative to 2020 without the bypass sand source to offset El Niño and sea level rise-related losses.

Nourishment and bypass potentially may lead to similar beach width changes in 2050

Our projections are expanded to include an alternative management strategy where sand nourishment replaces yearly bypassing. In this hypothetical scenario, nourishment is performed every five years at an equivalent cumulative bypass volume. Figure 6 illustrates that the nourishment vs. bypass scenarios result in a similar change in beach width, even if the trajectories are slightly different. Cost, sand availability, and logistical considerations would likely determine the most viable option, but the results demonstrate that a steady rate of yearly bypass and periodic nourishments achieve a similar accreting beach width during the 2020-2050 period.

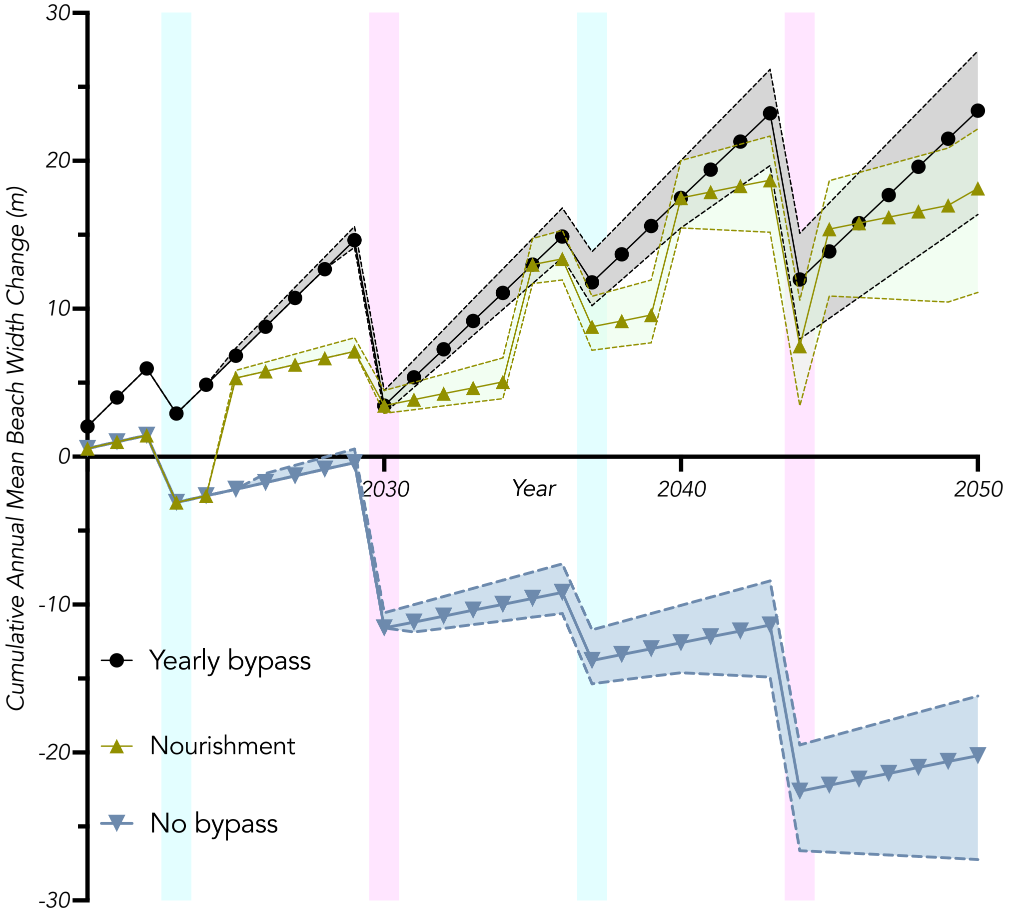

Figure 6: Bypass, nourish or no bypass impact on projected mean beach width change.
Yearly bypass vs. nourishment (every five years, no bypass) are compared to the no bypass scenario. Lines and ranges denote median and range across the low, intermediate, and high sea level rise scenarios. Pink and blue shaded areas represent El Niño years, pink being the "strong" years.

Sea level rise scenario is a key determinant for beach-width change

Low (0.3 m), intermediate (1.0 m) and high (2.0 m) scenarios are evaluated to assess the contribution of sea level rise to beach width change, shown in Figure 7. The percentage of beach width loss associated with sea level rise-equivalent loss increases from the low (14%), to intermediate (27%), to the high scenario (49%). The mean beach width changes in 2050 decrease from 27.4 m to 16.4 m from the “low” to “high” sea level rise alternative, with an increase in corresponding variabilities of prediction. The impacts will increase accordingly as sea level continues to rise after 2050.

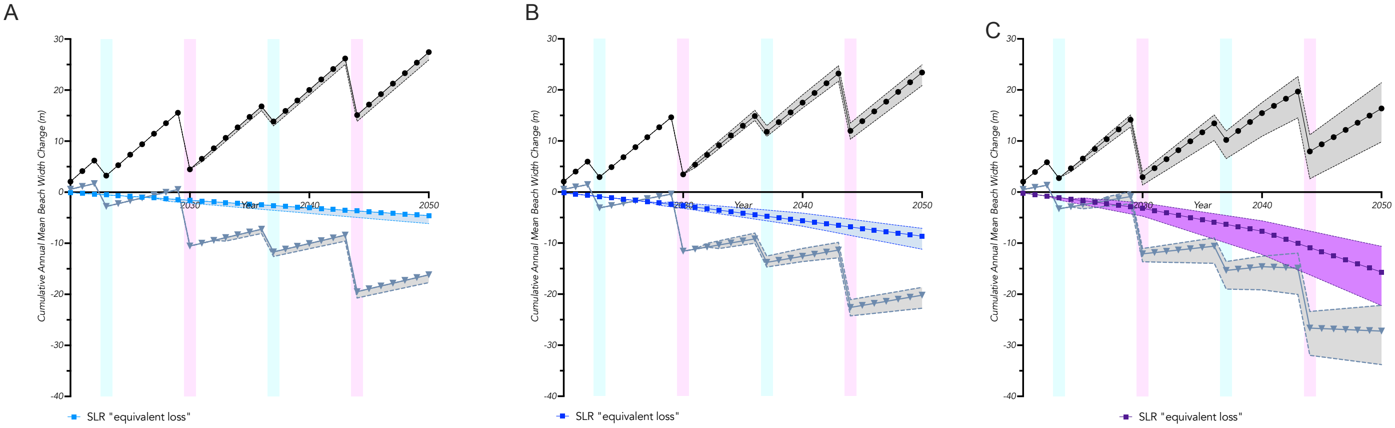

Figure 7: Sea level rise scenarios
Figure denotes three scenarios: low (A), intermediate (B), and high (C). Lines and ranges represent median and 15th and 83rd percentiles for each case. Blue and pink bars correspond to El Niño years, with pink denoting the stronger ones.

Frequency of strong El Niño events impact extent of beach width change

El Niño impacts are evaluated for once in seven- or ten-years cadences, with every other El Niño assumed to be “strong”. These cases were chosen based on historical observations of strong El Niños along the California coast[9]. The Multivariate ENSO Index (MEI) time series and the Oceanic Niño Index (ONI) are used to estimate historic ENSO variability[9,12,13]. Based on these metrics, the three strongest El Niño events occurred in 1982/83, 1997/98 and in 2015/16, with the spacings of 15 and 18 years (the MEI series was evaluated from 1871, and the ONI dating back to 1950)[9]. Results shown in Figure 8 point to a ~50% increase in mean beach width change in 2050 between the two scenarios, with the additional El Niño event taking a toll on the beach width in a pronounced manner particularly in the “no bypass” situation.

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[12] Wolter, K., & Timlin, M. S. (2011). El Niño/Southern Oscillation behavior since 1871 as diagnosed in an extended multivariate ENSO index (MEI. ext.). *International Journal of Climatology*, *31*(7), 1074-1087

[13] NOAA Climate Prediction Center; http://www.cpc.ncep.noaa.gov

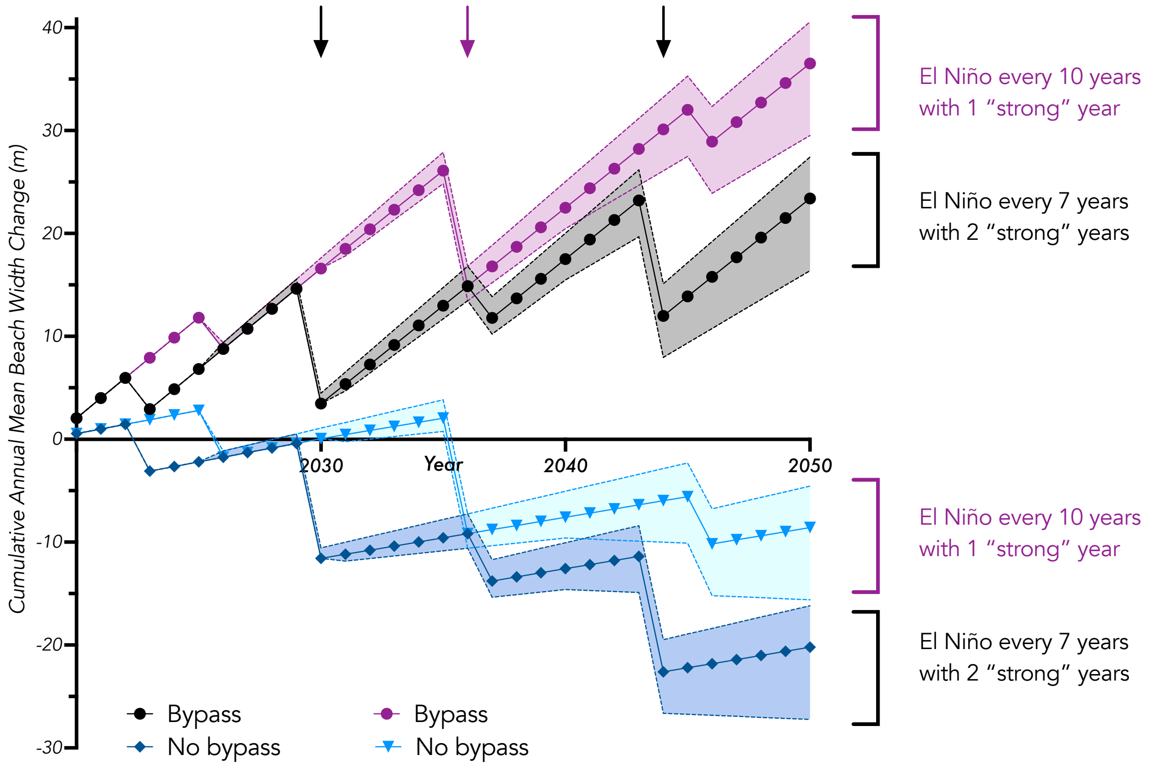

Figure 8: Impact of El Niño frequency on beach width change.
Yearly bypass vs. no bypass cases are compared across two El Niño frequency cases. Color-coded arrows correspond to strong El Niño years for each case. Lines and ranges denote median and range across the low, intermediate, and high sea level rise scenarios.

6. Discussion

California's coastal communities and infrastructure are increasingly vulnerable to climate change with increasing erosion and concurrent sea level rise[14]. Reliable and quantitative predictions of near- and long-term coastal changes are critical to inform coastal management activities and adaptation planning. Beach width change, particularly beach retreat, has serious implications on recreational activities, infrastructure, habitats, ecosystems as well as property along the coast. Southern California beaches have been sustained and enhanced for several decades through nourishment, lagoon dredging and sediment stabilization devices[15]. More recently, nature-based solutions such as living shoreline elements have been incorporated into

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[14] IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

[15] Flick, R. E. (1993). The myth and reality of southern California beaches. Shore & Beach, 61(3), 3-13

coastal resilience designs[2,16]. This report is focused on Cardiff State Beach in Encinitas, CA, which has had each of the above approaches implemented over the course of the last few decades. Effectively implementing these multi-pronged approaches requires strategic, data-driven collaborations across multiple stakeholders. The study described here provides some of the key pieces to form the basis of such collaborations.

The geographical compartmentalization of southern California establishes the concept of littoral cells or systems which have a source, a sink and/or a storage mechanism for sand, with limited exchange across cells. Here, a smaller subset of the Oceanside Littoral Cell is analyzed. A sediment budget model is used in CSB, which is assumed to be a “closed” system or sub-cell of the larger Oceanside littoral cell. This assumption is based on observed multiyear behavior at CSB[3]. The beach report data show that during the 2007-2015 recovery period post El Niño, the increase in nearshore volume was balanced by the reported nourishment and bypass volumes, indicating retention of nearshore sand supply. The analysis in this report assumes that the sediment output to the south (Solana Beach) from the CSB sub-cell is zero. This 1-D model provides a sediment budget projection for 2022- 2050 that includes a nearshore volume change consisting of natural and anthropogenic sand supply, and medium-term processes such as ENSO cycle retreat and recovery and sea level rise. This approach is a simplified model - a hybrid of empirical/data-driven model and a process-driven model such as an equilibrium beach profile model[10,17,18,19,20].

Our results indicate that the consistent source of sand to CSB through routine bypassing will be the primary factor for stabilizing, or even increasing, the beach width over the next three decades. Even a reduced bypassing rate of 10,000 m^3 of sand is sufficient to “hold the line” at CSB through 2050 (depending as well on the number of strong El Niño events). In the absence of bypassing, an equivalent nourishment schedule could potentially restore beach width, but cost, quality of sand and logistical constraints of nourishment vs. bypass would dictate the preferred strategy. For instance, nourishment costs at CSB were approximately \$25 per m^3 of sand for a total of \$1.7 million during the Regional Beach Sand Project II in 2012[21,22]. In contrast, the yearly inlet maintenance of the San Elijo Lagoon costs ~\$5 per m^3 of sand[23].

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[16] Saleh, F., & Weinstein, M. P. (2016). The role of nature-based infrastructure (NBI) in coastal resiliency planning: A literature review. Journal of Environmental Management, 183, 1088-1098.

[17] Vitousek, S., Barnard, P. L., Limber, P., Erikson, L., and Cole, B. (2017), A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change, J. Geophys. Res. Earth Surf., 122, 782– 806

[18] Davidson, M. A., Splinter, K. D., & Turner, I. L. (2013). A simple equilibrium model for predicting shoreline change. *Coastal Engineering*, *73*, 191-202.

[19] Fletcher, C., Rooney, J., Barbee, M., Lim, S. C., & Richmond, B. (2003). Mapping shoreline change using digital orthophotogrammetry on Maui, Hawaii. *Journal of Coastal Research*, 106-124.

[20] Ludka, B. C., Guza, R. T., O'Reilly, W. C., & Yates, M. L. (2015). Field evidence of beach profile evolution toward equilibrium. Journal of Geophysical Research: Oceans, 120(11), 7574-7597

[21] Coastal Regional Sediment Management for the San Diego Region, San Diego Regional Beach Sand Project II: https://www.sandag.org/uploads/projectid/projectid_330_9013.pdf

[22] Griggs, G., & Kinsman, N. (2016). Beach widths, cliff slopes, and artificial nourishment along the California coast. Shore Beach, 84(1), 1-12

[23] Leslie, B. Cardiff Beach Living Shoreline Year 3 monitoring report, April 2022, GHD. Personal communication

In the absence of human intervention in the form of added sand, El Niños and sea level rise take a toll on the beach width, decreasing it by ~25 m by the end of the three decades. Sea level rise is a crucial player particularly towards the latter half of the analysis timeframe. An intermediate sea level rise scenario accounts for ~30% of loss in beach width at the end of three decades. However, with sand supply from regular lagoon maintenance, it appears that the impact of sea level rise is likely manageable in this specific study area with the sub-littoral cell assumptions outlined in the report. These findings are in line with observations from the CSB report with a positive beach width trend (+4 m/year) since the 2015-16 El Niño[3]. The alignment of our hindcast with reported datasets from SIO and SANDAG is a promising finding from this study. In addition, the results suggest that the twice annual surveys conducted by SANDAG provide a good measure of annual beach change compared to the more densely sampled SIO data.

The stored dune sand in the living shoreline at CSB is another critical piece of the sand budget. The dune elevation has been unchanged since its construction in 2019, but its toe was damaged during “energetic”, but not extreme oceanographic conditions in the 2020-2021 winter[23]. Severe El Niño years are expected to undermine portions of the dune, based on eroded beach profiles from previous El Niños, thereby adding sand to the nearshore zone. In 2021, 5000 m^3 of the bypassed sand from the San Elijo Lagoon was used to repair the dune toe, with the remainder of the bypassed material placed in the intertidal zone of the beach. The interplay between dune restoration and beach placement of bypassed sand will be a key consideration in future adaptive management efforts for the dunes.

7. Conclusion

This report summarizes preliminary findings from a sediment budget model prediction of beach width change in Cardiff State Beach. The data emphasize the role of the regular, steady supply of bypassed sand from the San Elijo Lagoon as a key player in stabilizing and enhancing the beach width. The movement of sand between the dunes and the nearshore zone is a novel element of this model that needs to be assessed further during future El Niños or other highly energetic winter wave seasons.

8. Acknowledgement

The datasets used in this study were obtained through support from the United States Army Corps of Engineers, California Department of Parks and Recreation, Coastal Data Information Project (CDIP) and SANDAG. Thanks also to the many who provided the foundation for this work with 20+ years of data collection and storage including the field crew, lifeguards, surfers, city managers, SIO administrators and additional partners. Thanks to Bill O’Reilly for developing the sediment budget model and providing processed datasets, and to Coastal Processes Group for their valuable feedback. A big thanks to my CAC for their guidance and suggestions on this report.

Appendix A Sediment budget variables and estimates

The terms in the X_{MSL} equation are defined and estimated as follows:

C_{Equil} = Conversion from beach volume to beach width change
- = X_{MSL}/V the ratio of the change in the X_{MSL} location to the change in nearshore volume
- Estimated using SIO data for the 2010 and 2015 recovery periods to be 1 m/13,300 m^3.

V_{Bypass} = Annual bypass volume from San Elijo Lagoon inlet
- Assumed to include any alongshore transport into the nearshore zone from the north.
- Assumed to be zero during strong El Niño (used to rebuild Living Shoreline dune instead).
- Average bypass volume from 1998-2017 is 16,400 m^3. 20,000 m^3 is used as a yearly bypass approximation. A reduced 10,000 m^3 is used for the half-bypass case.

$V_{Nourish}$ = Annual sand nourishment volume placed seaward of the dune.
- Distinct from bypassing.
- Recent nourishment for CSB occurred as part of the Regional Beach Sand Project RBSP (RBSP)[4]
- Assumed to be zero, or five times the bypass amount (100,000 m^3) every five years.

$V_{ElNiño}$ = Nearshore zone volume loss during strong El Niño years
- Estimated from SIO nearshore volume change between 2015 and 2016 to be 100,000 m^3.
- Sand is assumed to be lost offshore of the nearshore zone or to the south of the beach.
- Zero for all moderate El Niño years (sand was observed to stay within the nearshore zone during the moderate 2010 El Niño).

V_{Dune} = "stored" dune volume shoreward of normal seasonal profile changes.
- Sand above natural maximum deposition elevation of the summer waves.
- See Appendix B for details on estimation and approximations.
- Living shoreline dune assumed eroded completely into nearshore zone during strong El Niño years.
- Mitigates $V_{ElNiño}$ loss but requires managed replacement using bypass sand after strong El Niño.

$\Delta X_{ElNiño}$ = Retreat of annual mean shoreline during El Niño year (moderate or strong)
- Associated with sand that remains within the nearshore zone (as opposed to net loss associated with $V_{ElNiño}$).
- Assumed to be -5 m during an El Niño year.

$\Delta X_{Recovery}$= Natural wave-driven recovery of mean shoreline between El Niño winters

- Represents multiyear shoreward migration of sand from the outer nearshore to the beach
- Conditional on mobile sand available in the nearshore zone
- South Torrey Pines "Control Beach" estimates this to be +1m/year[3], and approximated conservatively to 0.7 m/year[3,5].

ΔZ_{SL} = Yearly projected change in mean sea level[6]

β_{MSL} = Mean annual slope of the shoreline at MSL

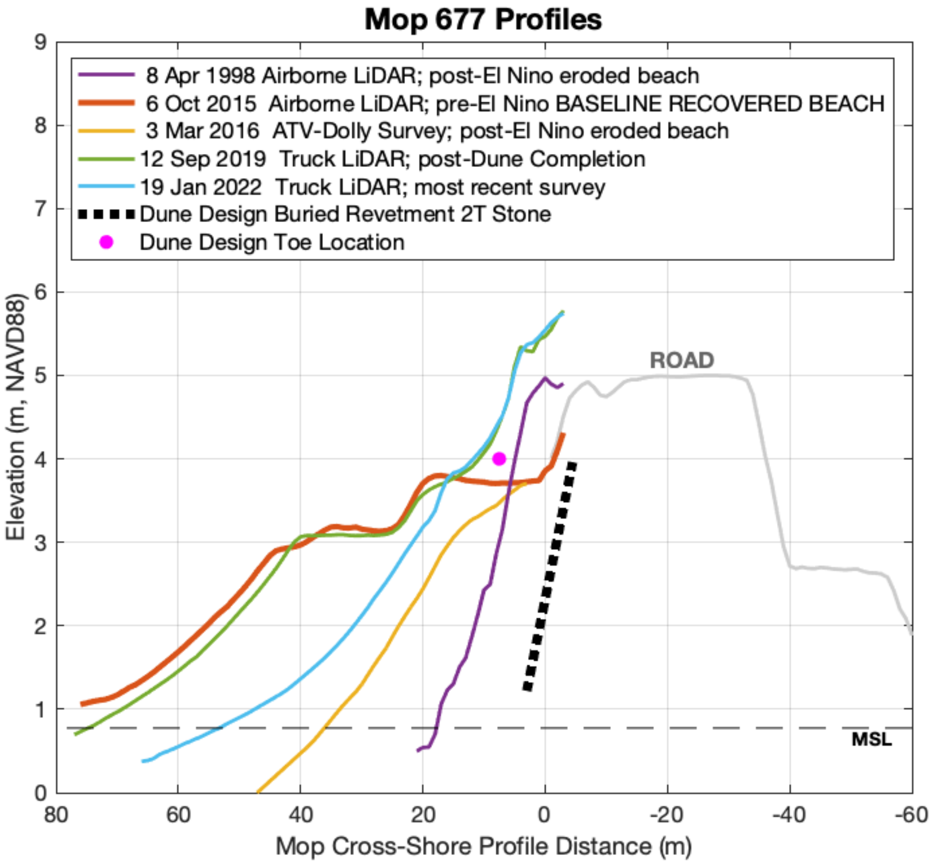
- 1/50=0.02 for Cardiff State Beach

V_{SL} = Sea level rise equivalent volume loss

- Long-term trend term that can alternatively represent "equivalent nearshore mobile sediment volume loss" owing to the increase in the mean depth of the entire profile)
- $= -C_{Equil} [\ \beta_{MSL} / \Delta Z_{SL}]$

Appendix B Dune "stored sand" calculation (estimating V_{Dune})

For the sand budget model shown in Figure 2, V_{Dune} is defined as the sand that is above the natural, wave-driven fully accreted beach observed with airborne LiDAR by the SIO Air-Sea Interaction Laboratory on Oct 6, 2015, prior to the 2015-16 El Niño winter. October 2015 was the end of a 5.5-year beach recovery phase after the 2009-10 El Niño winter (the same period used to estimate C_{Equil}). The resulting back beach elevation of the 2015 fall survey is assumed to represent the maximum natural dune height that the local wave climate and tide range can deposit over an ENSO beach recovery phase. Monitoring and Prediction (Mop) profiles were used to estimate dune volume. Figure below shows Mop 677 profiles that were used to analyze V_{Dune}[5].



"Stored" dune sand is defined as the portion of the current sand profile (blue line) above the baseline (red line, which is the Oct 2015 fully recovered natural back beach terrace). Eroded profiles from the 1997-98 and 2015-16 El Niño winters (purple and yellow lines) indicate that the dune may be undermined during a strong El Niño winter and the stored sand would then be "added" to the active nearshore zone. V_{Dune} is calculated to be 21,918 m^3 from 1/19/2022 truck LiDAR survey relative to the 10/2015 baseline survey[18]. This is close to the reported 22,937 m^3 of native dredged sand used in the project between November 2018 and June 2019[2]. For the analysis presented in this report, V_{Dune} is approximated to be 10-15 m^3/m-shoreline (20,000 m^3 for the entire beach length).

Appendix C Validation datasets

Year	Bypass	Nourishment	Beach width	Beach width	Offset Beach width	Offset Median width	Model hindcast
	m^3	m^3	SIO	SANDAG Median	SIO m	SANDAG m	Xmsl
	V bypass	V nourish	m	m			m
2000	17583.5	0		24.8		-8.6	2.0
2001	17583.5	77200		29.4		-4.0	9.7
2002	13761	0	36.2	37.0	16.4	3.6	11.3
🟦 2003	24464	0	25.4	40.2	5.6	6.8	8.7
2004	22935	0	39.7	42.4	19.9	8.9	11.0
2005	12996.5	0		53.3		19.9	12.7
2006	13761	0	35.5	41.3	15.7	7.9	14.2
2007	14525.5	0	42.9	53.0	23.1	19.6	15.9
2008	17583.5	0	34.6	41.8	14.8	8.3	17.8
2009	14525.5	0	41.4	52.4	21.6	19.0	19.4
🟦 2010	16054.5	0	36.7	50.9	16.9	17.5	16.1
2011	17583.5	0	41.5	50.9	21.7	17.5	18.0
2012	18348	68000	44.6	57.8	24.8	24.3	25.1
2013	19877	0	54.2	64.2	34.4	30.7	27.1
2014	17583.5	0	56.7	59.9	36.9	26.4	29.0
2015	16819	0	56.9	69.6	37.1	36.2	30.8
🟥 2016	16819	0	47.5	59.9	27.7	26.4	19.5
2017	12996.5	0	48.2	62.2	28.4	28.7	21.0
2018	0	229350	66.6	72.8	46.8	39.4	38.8
2019	0	18000	63.8	80.2	44.0	46.7	40.7
2020	0	0		71.6		38.2	42.8
🟥 Severe El Nino year							
🟦 Moderat El Nino							