Title
Lines in the Sand: The Challenges of Beach Width as a Parameter for Coastal Vulnerability

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The Challenges of Beach Width as a Parameter for Coastal Vulnerability

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ABSTRACT

As local coastal management in San Diego begins to develop climate change adaptation plans to address growing coastal vulnerability, beach width, the distance between the shoreline and the landward limit of the backshore, is growingly being cited as a metric for evaluating coastal vulnerability and triggering a more aggressive adaptive response. This is because narrowing beach width could serve as an early warning indicator of long-term beach erosion or permanent beach loss. The beaches may also serve as a buffer against coastal hazards such as king tides, wave energy and sea-level rise for coastal homes, businesses, or infrastructure. This study assessed spatio-temporal trends associated with the natural variability of beach width and identifying deviations from the norm. The analysis was conducted using 8 years(2008-2016) of monthly beach width data collected by the Scripps Institution of Oceanography, from two locations in San Diego – Imperial Beach and North Torrey Pines and compared with quarterly beach surveys at the same locations for the SANDAG Regional Shoreline Monitoring Program. Additionally, this study will highlight the importance of El Niño seasons and beach nourishments on beach width variability, and how these factors might be considered when establishing a beach monitoring approach and setting triggers for implementing an adaptive response.

KEYWORDS

Beach Width; Beach Monitoring; Coastal Vulnerability; Trigger; Threshold; Baseline; Coastal Erosion

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INTRODUCTION

In San Diego County, coastal vulnerability is becoming more apparent as climate change-related sea-level rise (SLR) and coastal erosion increasingly threaten the existence of iconic beaches, infrastructure, and homes. According to California's 4th Climate Change Assessment, the San Diego County coastline is expected to experience 1 ft of SLR by mid-21st century, and 3 ft or greater by 2100 (California 4th Climate Change Assessment - San Diego Region Report 2018, pg 39). When coupled with phenomena such as high tides and seasonal storms, these coastal hazards pose a growing threat to the well-being of local coastal ecosystems and communities. Thus, many cities along the San Diego coast have already started to consider long-term solutions and adaptations for future coastal hazards. These plans are typically disclosed in documents known as Climate Adaptation Plans or Resiliency Plans.

These plans elaborate on the goals and preferred methods of adaptation specific to each city and are commonly integrated under their individual Local Coastal Programs(LCPs), which are planning tools used by local governments for coastal development in coordination with the California Coastal Commission. A common component of a climate adaptation plan is the establishment of adaptation pathways (APs). APs use indicators of change such as flooding, beach width or storm events, to signal the need to take timely adaptive actions before a coastal hazard reaches a tipping point, also known as a threshold, for risk to property, people, or a natural ecosystem(Stephens et. al. 2018).

Beaches are not only hubs for business and recreation, driving an important part of the local economy, but they also serve as a buffer between the ocean and the inland area. As sea level rises, beaches are expected to narrow, reducing the effectiveness of this buffer. Therefore, beach monitoring programs are expected to play an important role in future coastal planning and management. In the San Diego State Lands Sea Level Rise Vulnerability Assessment, *beach width*, which typically refers to the horizontal distance between the shoreline position at mean sea level and the landward limit of the backshore (Coastal Engineering Research Center 1991), is mentioned as a method for measuring a beach threshold which would trigger an adaptive responses(San Diego State Lands Sea Level Rise Vulnerability Assessment 2019). This study we considers beach width as an indicator of beach change and associated coastal hazard risk, and highlights some considerations for establishing a monitoring approach.

BACKGROUND

1.1 Thresholds & Triggers

Many ecological and environmental studies have shown that most natural systems on Earth have tipping points that when crossed, lead to nonlinear changes in the system's function and capacity (Kelly 2015). The response to approaching one of these thresholds can be fundamental when designing environmental policy and management practices (Kelly 2015, Stephens et. al. 2018). This is why policymakers and environmental managers often look for triggers, which are predefined events or changes in the status of the system, that provide forewarning of when thresholds are close to being reached (Nie & Schultz 2012, Stephens et. al. 2018). Triggers indicate potential risk and act as a signal for an immediate review of the current management action in order to prevent potential damage to the system and avoid any negative associated consequences. Therefore, identifying thresholds and triggers has become increasingly relevant in environmental management as many of Earth's natural systems are being threatened by anthropogenic climate change.

When applied to the topic of coastal vulnerability, beaches are key systems that protect the coastline from a variety of coastal hazards. Beaches are not only places of recreation and commerce but they can also act as physical buffers by absorbing and dissipating the energy from breaking waves, helping to stabilize the shoreline and minimize the impact of coastal flooding. However, as the sea level rises, areas along the coast, including beaches, are at increased risk for erosion. Beaches are dynamic systems, fluctuating in size and shape over time, depending on nearshore hydrodynamics and changes in sea level and sediment supply (Alexandrakis & Poulos 2014). All of these processes play a part in the maintenance of the beach, and if altered or interrupted, can have impacts on the shape of the coastline and its level of resilience to coastal hazards. In San Diego, the prevalence of coastal armoring (e.g. seawalls, breakwaters) and the urbanization of watersheds have led to many beaches being sediment starved (Flick, 1993; Slagel & Griggs 2008). Here, the natural flow of sand is altered and sediment ends up accumulating behind dams and other urban infrastructure instead of being transported to the shoreline. This has placed many beaches along the San Diego coast at higher risk for erosion and adds to overall coastal vulnerability in the region.

Consequently, there is growing recognition that beaches are at risk due to increasing erosion and sea-level rise, and that beach width is a useful parameter for city managers to monitor the extent of this risk. Although beach width does not account for the volume of sand or the elevation of a beach area, it is generally assumed that the wider the beach, the more space there is between developed areas and the ocean, and the more likely that the beach can effectively reduce the impacts of coastal hazards. Setting beach width as a parameter and establishing trigger points allows for coastal managers to recognize when the beach system might be approaching its capacity for coastline protection and hopefully can prompt precautionary action to preserve the beach and, or coastal infrastructure.

The effectiveness of selected triggers depends on the degree of cautiousness considered and the amount of available information about the historical and current state of the beach and associated nearshore processes. Discerning when a trigger has been reached will involve an assessment of natural fluctuations in the beach, which for San Diego will include changes due to heavy wave activity during El Niño winters (Flick 1998; Barnard et al. 2017; Young et al. 2018). Large storm events can result in dramatic narrowing of the beach profile as sand moves to deep water. During extended periods of stormy weather, such as El Niño winters, beaches experience significant increases in erosion and recovery can be slow, or irreversible due to the permanent loss of sand (Inman 2003). Years of energetic winter wave conditions are important in assessing triggers. For example, a large narrowing of the beach in an El Niño winter may be followed by a rebound during summer wave conditions, and hence a trigger is not necessary, or it may indicate a shift toward a more permanent eroded state. This then poses the question of how long one should wait to recognize the shift to initiate a trigger.

1.2 El Niño

El Niño refers to the large-scale, coupled ocean-atmosphere climate mode, characterized by unusually warm sea surface temperatures in the central and east-central Equatorial Pacific. These warmer temperatures and changing wind patterns affect mid-latitude storm patterns, and so a tendency for more frequent and stronger storm-driven swell waves in Southern California during the winter months of an El Niño event. The unusually strong wave action leads to increased erosion and significant amounts of beach sand transport to deep water. Therefore, beach width is expected to take a sharp decrease during this period of exceptionally stormy weather, potentially contributing to permanent loss of sand (Inman 2003).

1.3 Beach Nourishment

With the projection of accelerated sea-level rise and dwindling sand supplies, it is likely that beach nourishment will become more prevalent as managers seek to protect the coastline. Beach nourishment is the practice of adding significant quantities of sand or sediment to beaches in an effort to combat erosion and increase beach width and volume. Based on projections of accelerated sea-level rise and possible coastal storm intensity, cities in San Diego County such as Imperial Beach (Revell Coastal & City of Imperial Beach 2016) and the city of San Diego(City of San Diego State Lands Sea Level Rise Vulnerability Assessment 2019) are looking to beach nourishment as the primary climate adaptation strategy to slow erosion and protect the coastline. However, beach nourishments can be expensive, as they are major engineering projects that require not only a significant source of sand at the appropriate grain size, but also the heavy machinery used to transport and distribute new sand.

The current adaptive pathway for protecting a beach likely involves a series of beach nourishment projects, which themselves might be initiated and evaluated using beach width. At some stage, beach width might narrow to a point where ongoing nourishment alone may not be practical or effective. This would then trigger a change in adaptive strategy, perhaps to dune hardening projects or seawalls. Further sea-level rise and narrowing of the beach might push these projects toward their thresholds, triggering more aggressive measures, such as the relocation of assets and the establishment of setbacks.

1.4 Significance of Problem

Challenges involved in using beach width as a trigger metric include determining natural variability and identifying a baseline, which is the starting point from which the metric of change is calculated. Ideally, baselines would incorporate information on historical trends to provide an extrapolated forecast that shows where the beach might be headed if no changes are made to the current system. In the case of beach width, baselines allow for management to assess the state of the beach and can be used to gauge when or where to set a trigger. The baseline is calculated from measurements of beach width over time. However, the beach width varies with episodic changes in waves, tides, and seasonal and climate patterns (e.g., El Niño events). Thus, the baseline will vary depending on the time and space scales included in its calculation. The baseline is also influenced by the spatial and temporal extent of the measurements. Bathymetric features (e.g. canyons, rocky reefs) can influence the wave energy and wave direction at the shore, forcing that largely controls the rate of erosion and movement of sediment on the beach. Therefore, some areas of a beach may experience greater rates of erosions than others. The greater the number and frequency of accurate measurements, the higher the accuracy of the baseline as representative of beach width conditions for that specific site. Since triggers are based upon the knowledge of the natural capacity and variability of the system, establishing triggers within the context of beach width can be difficult without a strong grasp of what the baseline should look like.

Another challenge for using beach width as a parameter, is the process of beach monitoring and surveys. Beach surveys can be laborious, time-consuming, and can require specialized equipment. Monitoring requires regular and continuous surveys in order to obtain consistent data to track the state of the beach. Since most cities in the region have only just recently updated their adaptation and resiliency plans to include beach width, the integration of beach monitoring is still fairly new and can be sparse due to limited resources. This raises the issue of what can cities effectively capture about beach width and its trends with limited monitoring.

1.5 Local Beach Monitoring

1.5.1 Beach Monitoring by Scripps Institution of Oceanography

Since 2001, scientists from the Integrative Oceanography Division at the Scripps Institution of Oceanography have regularly monitored several beaches along the San Diego coast to study beach change and nearshore processes. The first study site was established in 2001 at Torrey Pines, followed by Cardiff in 2007, and Solana Beach and Imperial Beach in 2008. These monitoring sites range from 4 to 8 km in alongshore length. Monthly beach surveys are ongoing at fixed transects (Figure 1) with a minimum alongshore resolution of 100 m (Ludka et al. 2019). Wave buoys maintained by the Coastal Data Information Program, and a local tide gauge maintained by the National Oceanic and Atmospheric Administration, complement the sand level observations. The dataset represents a unique resource for assessing beach change over nearly two decades at high temporal and spatial resolution sampling.

1.5.2 SANDAG Regional Shoreline Monitoring Program

Beginning in 1996, the San Diego Association of Governments (SANDAG) has funded the Coastal Frontiers Corporation to conduct semi-annual beach surveys during the spring and fall, with the goals of documenting changes in beach width over time, evaluating the benefits of sand replenishment projects, and helping to improve the design and effectiveness of beach fills. The surveys are currently conducted in 39 locations, along a total of 54 cross-shore transects. The spacing between surveys is typically 1 km or more.

1.6 Statement of Purpose

This study aims to assess the natural variability of beach width at two beaches in San Diego County and to identify any notable changes or deviations from this norm trend that should be considered in establishing a monitoring approach and triggers. This is accomplished through statistical time series analysis of Scripps beach width datasets, exploring data on a multi-year, annual and seasonal time scale. In particular, the study will also take into consideration El Nino events and beach nourishments as possible factors that could significantly impact observed changes in beach width and the calculation of the baseline. Additionally, this study will compare the Scripps monitoring data with beach width trends published in the San Diego Association of Governments(SANDAG) 2018 Regional Beach Monitoring Program Annual Report to further explore how well more limited beach survey methods can capture seasonal and annual beach width trends as well as impacts and beach response from extreme events such as El Niño. Based on the results, this study will highlight considerations for establishing a monitoring approach and triggers based on tracking beach width.

METHODS

2.1 Study Sites

2.1.1 Imperial Beach

Located in the southwestern most corner of San Diego County is the city of Imperial Beach. With the Pacific Ocean to its west, the San Diego Bay to its north, and the Tijuana River to its southeast, the city is predicted to lose about a third of its developed land without any sea-level rise adaptive action. The city's primary concerns are flood-related due to the seasonal high tides and waves, with impacts affecting low-lying areas and the City's storm drainage system. Imperial Beach's 2016 Sea Level Rise Assessment (Revell Coastal & City of Imperial Beach 2016) projects flooding impacts from sea-level rise at 0.5 m (by 2047), 1 m (by 2069) and 2 m (by 2100). The report also recommends monitoring beach profiles to understand local variability in sand supply, and alongshore sediment transport and erosion (Revell Coastal & City of Imperial Beach 2016).

The three beaches that comprise Imperial Beach's shoreline are Imperial Beach City Beach, South Imperial Beach, and Border Field State Park Beach. This study will only examine data from Imperial Beach City Beach and South Imperial Beach. Imperial Beach City Beach is located between Palm Avenue and Imperial Beach Boulevard. It is about 820 m in alongshore length and borders the western part of the City of Imperial Beach. South Imperial Beach continues south of Imperial Beach Boulevard until the southern end of Seacoast Drive. It is about 2300 m in alongshore length and to its east are a narrow stretch of homes along Seacoast Drive and the Tijuana River Estuary. In 2012, the Imperial Beach shoreline received a nourishment of 344,000 m^3 of fairly coarse sand (Ludka 2019), placed along the southern portion of Imperial Beach City Beach and the northern portion of South Imperial Beach.

2.1.2 Torrey Pines

Located adjacent to the Los Penasquitos Lagoon and Torrey Pines Natural State Reserve, Torrey Pines State Beach is jointly managed by the State Reserve and by the California Department of Park and Recreation. The beach is 7240 m in alongshore length, stretching from the southern end of Del Mar to the cliffs at Torrey Pines Mesa. It is largely backed by cliffs and like the state reserve, the beach is used as an area of recreation, for activities such as surfing and swimming. The beach has historically experienced major erosion during storm events, that has resulted in unreliable access to the beach and connected trails. The most recent nourishment at Torrey Pines was in

April 2001, when 187,000 m^3 of sand was placed along a portion of the beach just south of the lagoon mouth (Ludka 2019).

In December 2019 the Los Penasquitos Lagoon Foundation was awarded grant funding for the *Torrey Pines State Beach Sea Level Rise Plan Adaptation Planning Projec*t, from the State Coastal Conservancy (Los Penasquitos Lagoon Foundation 2019). Although the proposed project does not mention beach width specifically, it does mention "outlining opportunities and constraints to construct innovative natural shoreline infrastructure to increase coastal resilience" (Los Penasquitos Lagoon Foundation 2019).

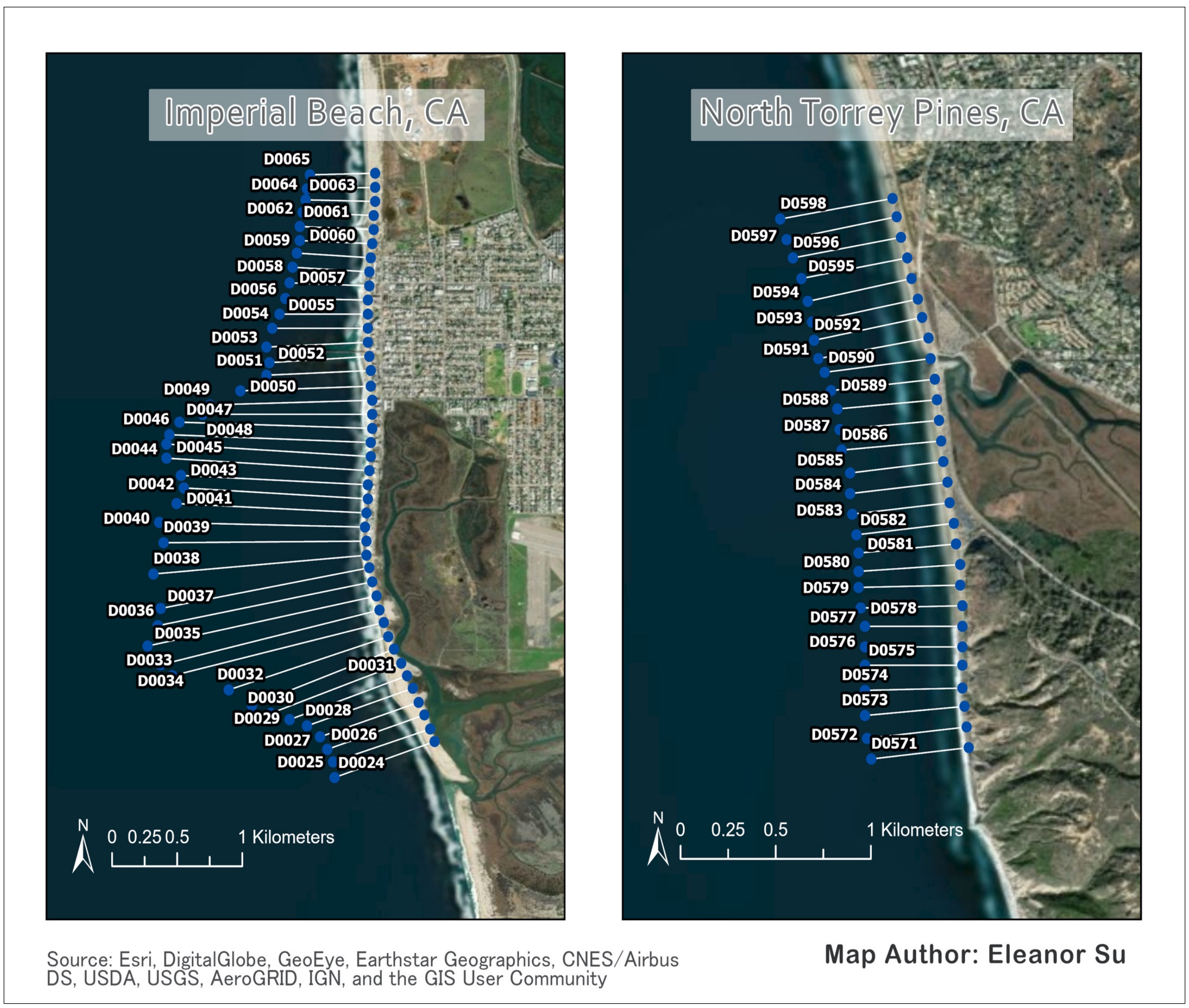

Figure 1. Map of Imperial Beach and North Torrey Pines, with Transect Position and Numbers

2.2 Beach Width Time Series

The beach width data utilized for Imperial Beach was calculated on 42 transects (D0024-D0065, Figure 1) spanning an alongshore length of approximately 4200 m, with a maximum of 95 beach width measurements in time made for a single transect. The data utilized for North Torrey Pines was calculated on 28 transects spanning an alongshore length of approximately 2800 m, with a maximum of 98 beach width measurements in time made for a single transect. For both sites, the frequency of these measurements was monthly, over 8 years (November 2008 - December 2016). Beach width was calculated at Mean Sea Level, which is the mean height of the surface of the sea for all stages of the tide over the National Tidal Datum Epoch (i.e. 19-year period adopted by the National Ocean Service).

2.3 Statistical Methods

Basic statistical analyses were applied to the beach width data using Excel by Microsoft and Matlab by MathWorks. These methods were organized into two sections. The first focused on describing the variability of the Scripps dataset, including space-time plots, spatial and temporal averaging, and definition of a seasonal cycle and anomaly. The second focused on comparing 1-km spaced transects collected at semi-annual surveys (SANDAG sampling) with the results from the higher resolution Scripps data.

RESULTS

3.1 Beach Width Variability

The spatial and temporal beach width fluctuations are illustrated by subtracting the time-averaged beach width calculated for each individual transect (Figure 2a & 2b). These figures show that temporal variations in beach width are more uniform along the beach at Torrey Pines, with Imperial Beach showing considerable variability, largely attributed to the 2012 nourishment, but apparent before the nourishment as well.

The alongshore averaged beach width is calculated as the spatial mean over all transects for each date of measurement. The mean beach width shows a seasonal cycle for both sites, with annual maxima typically during late summer to early fall, and minima during early spring (Figure 3). North Torrey Pines appears to have a more consistent cycle with the majority of values ranging between 25m to 45m, with a slight overall decreasing trend. Imperial Beach exhibits more dynamic variability, with minor fluctuations within its seasonal patterns, and an increasing trend. Before the 2012 nourishment, the majority of values range between 25m to 60m. After the nourishment, the majority of the values range between 45m to 75m. I will use the mean beach width as the indicator of change for both locations.

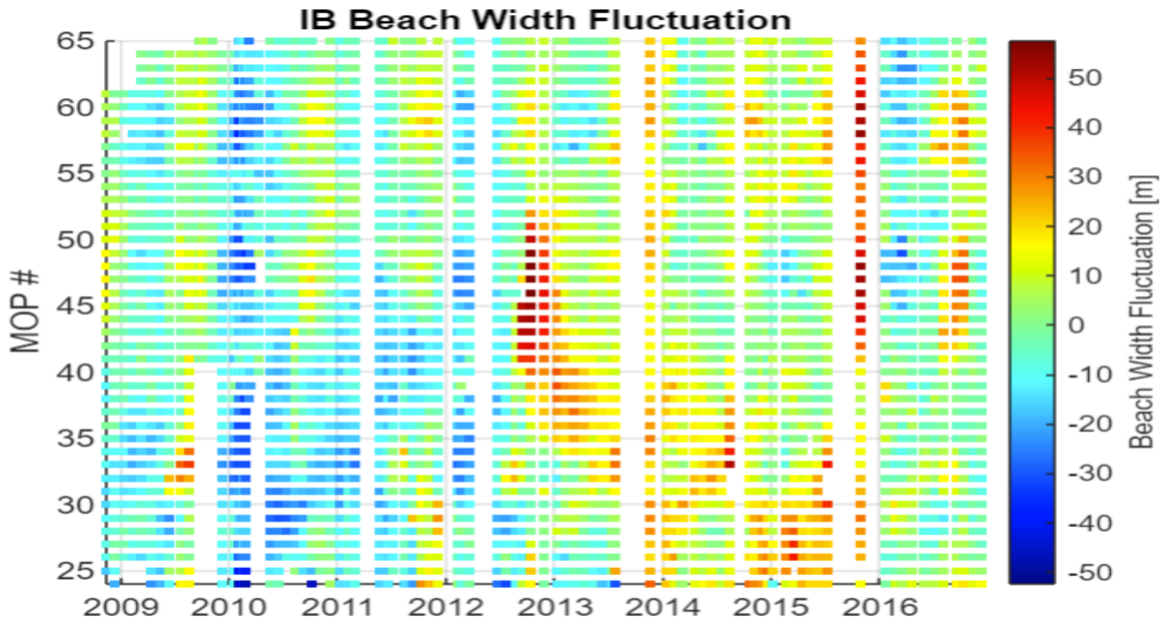

Figure 2a. Beach Width Fluctuation of Imperial Beach

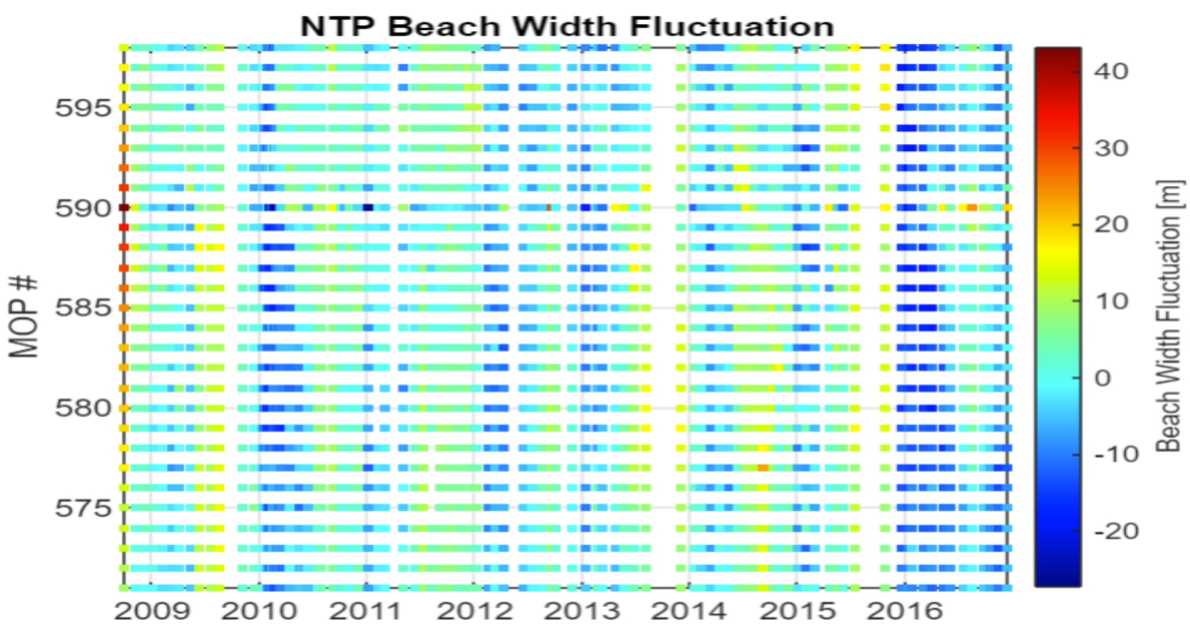

Figure 2b. Beach Width Fluctuation of North Torrey Pines

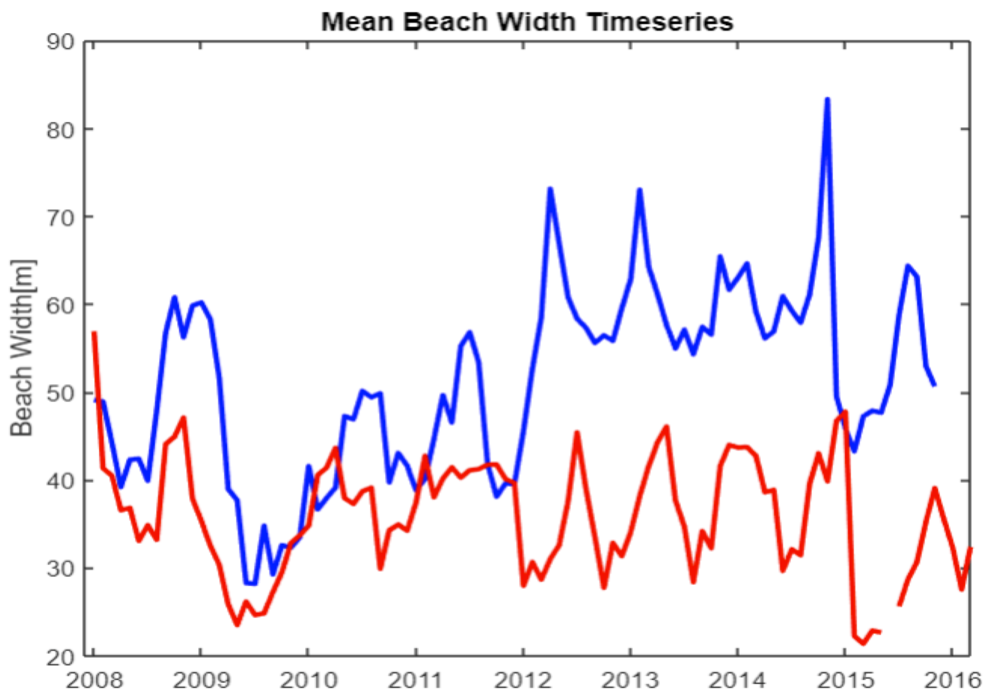

Figure 3. Mean Beach Width Time Series of Imperial Beach and North Torrey Pines

3.2 The Seasonal Cycle and Beach Width Anomalies

The average seasonal cycle was calculated by finding the month averages over all years (i.e., average of all Januarys, Februarys, etc…) of the mean beach width time series (Figure 4). For both sites, the highest value of annual seasonal cycle occurs during the latter half of the year, in October, representing the net buildup of the beach during summer wave conditions. The lowest value occurs in February for Imperial Beach and March for North Torrey Pines, after the peak winter wave season and maximum beach erosion. Imperial Beach is wider on average throughout the year than North Torrey Pines, which can be attributed in part to the 2012 nourishment.

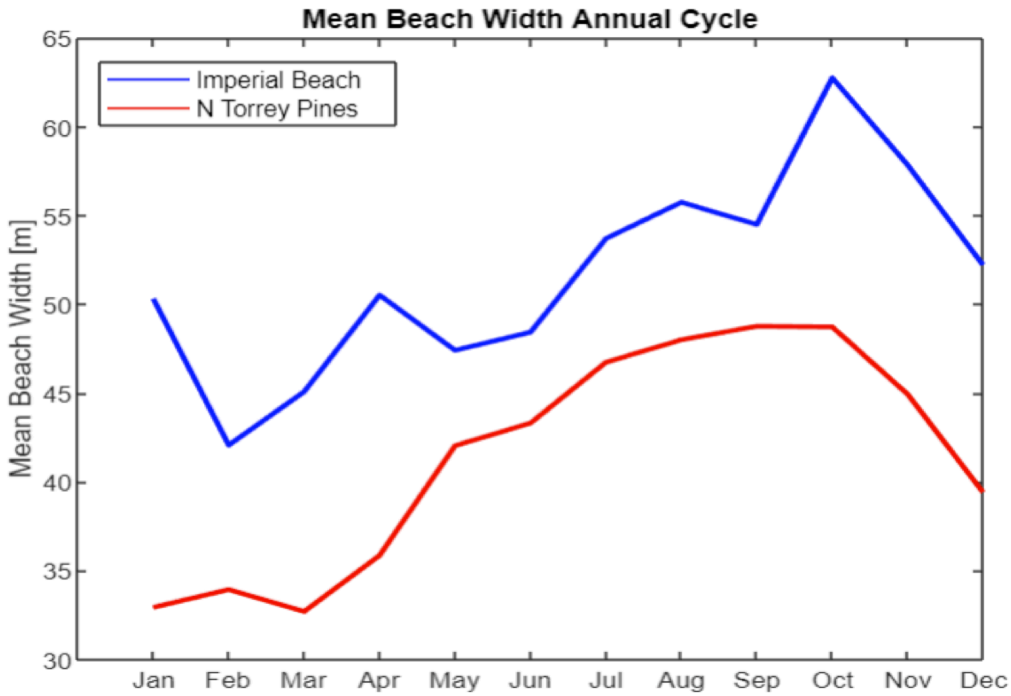

Figure 4. Annual Seasonal Cycle of Imperial Beach and North Torrey Pines

A beach width anomaly is calculated by subtracting the seasonal cycle from the monthly data, representing a deviation from typical seasonal behavior observed in the alongshore-averaged beach width time series (Figure 5). For North Torrey Pines, the range of anomalous values falls mostly between -15m and +15m, with a slightly decreasing overall trend. The most prominent shifts in values are observed as a decrease towards the latter half of the year in 2009 and 2015, during El Niño winters with energetic waves. Before 2015, the range of values mostly fall between -10m and +10 m from the mean beach width. For Imperial Beach, the range of anomalous values falls mostly between -15m and +20m of the mean beach width time series, with a positive overall trend. The most prominent shifts in values are observed as a decrease towards the latter half of the year in 2009 and 2015 during energetic El Niños, and an increase in the fall of 2012 due to nourishment. The nourishment shifted the range of values from -15m to +5m before mid-2012 to, -5m to +20m after mid-2012.

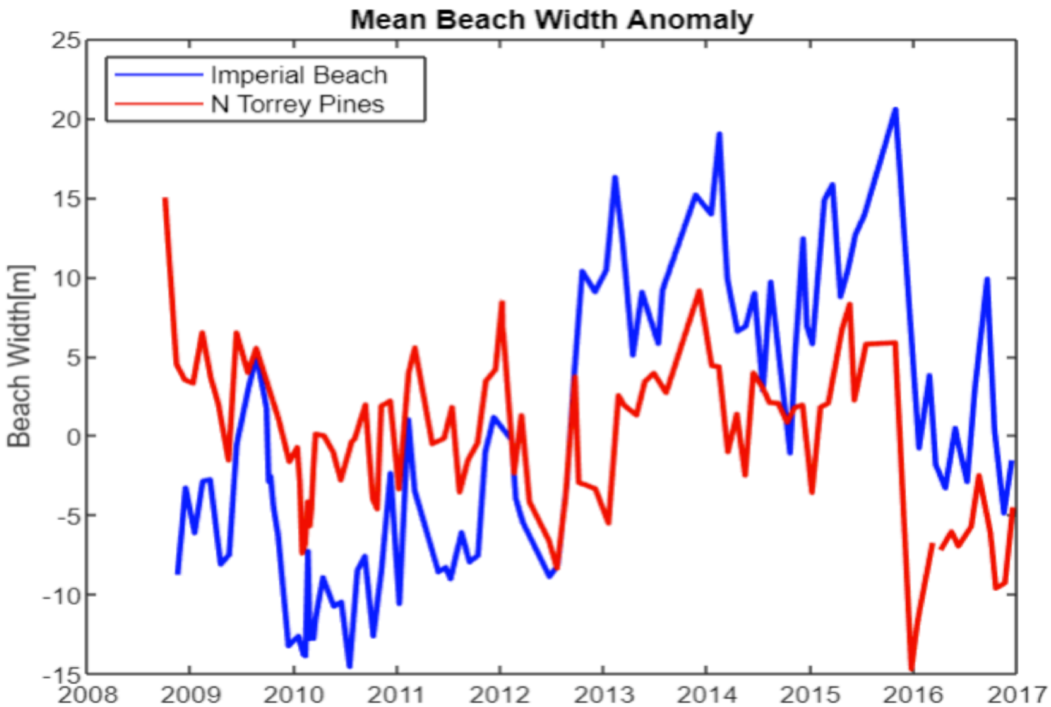

Figure 5. Time Series Anomalies of Imperial Beach and North Torrey Pines

I further smooth the data by computing a 3-month running mean of the anomaly time series, producing a quarterly mean beach width (Figure 6). The series exhibit similar year-to-year variation in beach width, including during the El Niño events, whereas the differences in overall trend are more pronounced.

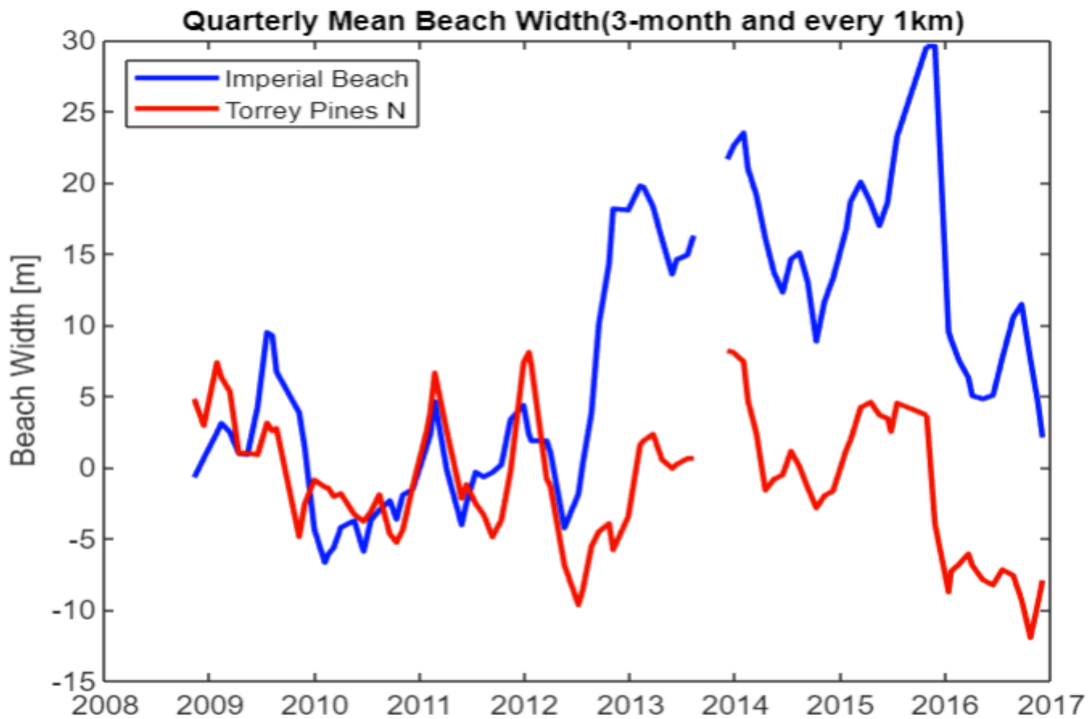

Figure 6. Quarterly Mean Beach Width Time Series of Imperial Beach and North Torrey Pines

The difference between the Imperial Beach and Torrey Pines quarterly anomalies (shown in Figure 6) highlights that the main difference between the sites is the 15m, step-like increase in beach width associated with the 2012 nourishment at Imperial Beach (Figure 7). The differencing reduces the year-to-year variability present in the individual quarterly records (Figure 6), suggesting that much of this variability is common between the sites, presumably because both sites experience similar wave forcing.

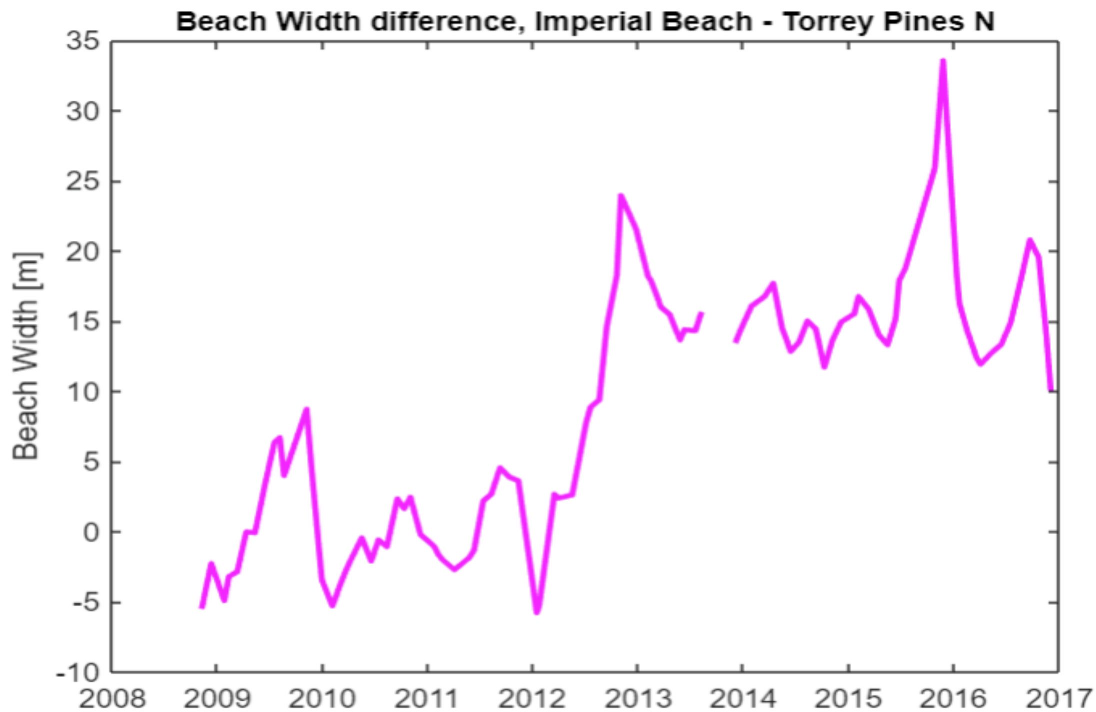

Figure 7. Difference between Imperial Beach and North Torrey Pines based on Quarterly Mean Beach Width Time Series

3.3 Subsampled Beach Width – How accurate is it?

Our main objective is to determine whether the SANDAG sampling of beach width, representing what a coastal municipality might be able to achieve, provides a reliable estimate of the beach width computed using the more comprehensive Scripps, research-quality data. For this assessment, I subsample the Scripps data following the sampling strategy of SANDAG. For this, I take an alongshore average of the Scripps data using a 1-km spacing, or one-tenth the resolution of the Scripps sampling. This results in a fall and spring value for each year. I remove the mean spring beach width from all spring values, and the same for fall values, to obtain an anomaly time series. I compare the resulting values to an annual mean beach width of the fully sampled Scripps time series in Figure 6. In this case, I assume that a city can afford a monitoring program involving a single beach width measurement period each year at 1-km spatial resolution. They would like to use the resulting alongshore average as a measure of the annual average beach width, a fairly stable indicator time series of beach width that captures phenomena like El Niño , and interventions like nourishments. From this more limited approach, can the resulting series be useful to identify triggers?

The results for the two locations suggest that conducting a monitoring campaign in the spring, representing the accumulative net erosion of the winter season, provides a reasonable estimate of the annual average (Figure 8a). The spring average captures the drop in beach width following the 2015-16 El Niño , the increase in width at Imperial Beach associated with the replenishment, and year-to-year fluctuations have a similar character, although these variations are higher in the spring time series than fall, particularly at Torrey Pines. The fall beach width time series does not track the annual average as closely as the spring time series. For example, the fall of 2015 shows an unusually wide beach at both sites that is not reflected in the annual average. These comparisons suggest that spring is the optimal time to conduct an annual monitoring survey, and that the results provide a reasonable proxy for the annual beach width.

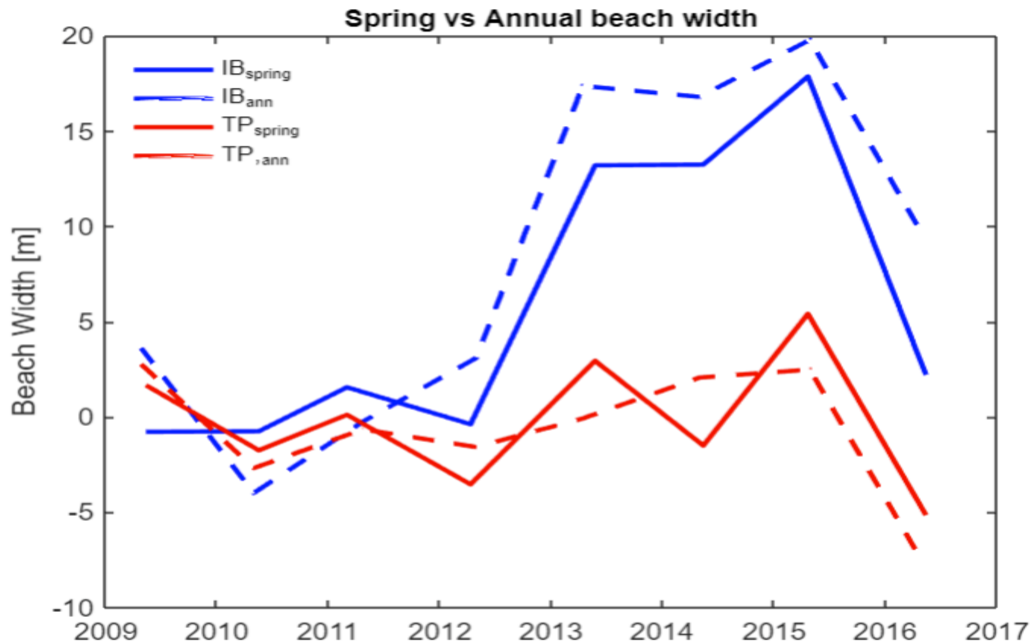

Figure 8a. spring vs. Annual Mean Beach Width for Imperial Beach and North Torrey Pines based on Quarterly Mean Beach Width Time Series

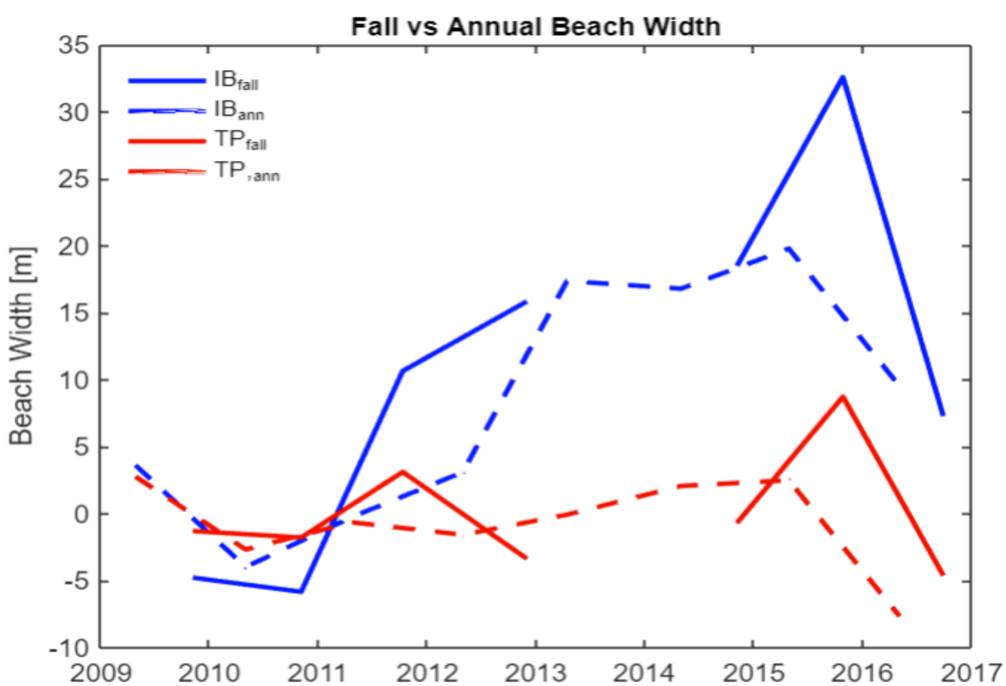

Figure 8b. fall vs. Annual Mean Beach Width for Imperial Beach and North Torrey Pines based on Quarterly Mean Beach Width Time Series

DISCUSSION

4.1 Findings

Beach width at Torrey Pines and Imperial Beach exhibit a prominent seasonal variation due to the seasonality of wave forcing. During summer, gentler waves deposit sand from offshore bars onto the beach, resulting in increased beach width and sand volume. The opposite occurs during winter, when stronger winter waves carry the sediment back offshore, resulting in the narrowing of the beach. This was demonstrated in the annual seasonal cycle(Figure 4) with the peaks occurring during early fall and the troughs during early spring for both North Torrey Pines and Imperial Beach.

We find that a single annual survey can provide a useful proxy for annual beach width. Not only did the Spring Mean plots more resemble the Annual Mean plots, but Spring is also right after the winter season which the beach experiences the most erosion. Therefore, by consecutively surveying in Spring, cities should be able to tell if beach width is generally stable from year to year or not. If the measurement is consistently decreasing after some number of years based on annual spring measurements, it would signal that the beach is continuously failing to accumulate as much sand in the summer that it lost in the winter.

Beach width varies from year-to-year. Notably, the beach narrows considerably between 2009 to 2010, and 2015 to 2016. This was observed in both Imperial Beach and North Torrey Pines and was likely due to enhanced wave conditions during these El Niño winters. During this time, elevated winter wave energy led to heightened rates of erosion and a sharp decrease in beach width and volume (Barnard 2017). This reaffirms the understanding that El Niño events have a significant impact on beach width, and so it is key that monitoring programs need to take these events into account when establishing triggers and setting baselines for beach width. Moreover, the El Niño year is likely to be a threshold year to plan for as this is when the beach reaches a highly eroded state. With El Niño events predicted to become more frequent in the future (Wang 2019), this could imply an accelerated decreasing trend in beach width in the future for the sites studied and possibly all beaches in the San Diego Region.

We observed a positive beach width trend for Imperial Beach and a negative trend for North Torrey Pines. Imperial Beach received a substantial nourishment of 344,000 cubic m^3 of sand in September 2012, yielding higher beach widths that persisted for four years. North Torrey Pines appears to be experiencing long-term sand loss, presumably due to the lack of natural sand supply. The Imperial Beach record emphasizes that nourishment can provide years of protective service. The nourishment provides immediate relief to any sort of long-term erosional trend such as observed at Torrey Pines, as well as a buffer to El Niño events. At Imperial Beach, the 2016 El Niño resulted in a return of beach width values that occurred prior to the nourishment. If a single El Niño can erase the benefits of nourishment project, then the projected El Niño index might prove useful as a trigger. That is, once El Niños are projected to become so frequent that nourishment projects become economically unviable, this might set off a trigger to move toward shoreline hardening solutions.

4.2 Limitations & Uncertainty

The study only looked at data from two study sites within the San Diego Region, whereby beach width trends observed are specific to these sites and do not necessarily mirror those of all other beaches in the region. Still, this study benefited from the availability of high quality, high resolution data collected by the Scripps Institution of Oceanography. Before extrapolating these findings to other beach sites, however, additional research is required. The comparisons should be repeated at other Scripps study sites, and a formal error analysis should be included in the results. The error analysis would be helpful in assessing the trigger. It may be that the average of the fall and spring surveys may prove more reliable than a single fall survey at Imperial Beach and Torrey Pines, as well as other sites. I did not consider this possibility due to an unfortunate data gap in the fall record. The effect of alongshore averaging, and the extent to which the averaging should be performed, are open questions. This study utilized records dating back to less than two decades. The earliest measurements for North Torrey Pines and Imperial Beach were in 2004 and 2008 respectively. Thus, triggers based on extrapolated trends are not recommended based on such a limited dataset. Also, the data only two El Niño events, and only one post event recovery period. Additional data are needed to investigate the ability of beaches to recover naturally following El Niños and other winters of energetic wave activity.

CONCLUSIONS

From this study, I conclude that for San Diego County beaches, beach width exhibits a fairly predictable baseline seasonal cycle, with highs in the early fall and lows in early spring. Thus, the goal of identifying anomalies and setting triggers accordingly should be reasonably achievable, and with single anomalous shifts becoming more clear as records grow over time.

Major forcing or intervention, like that from El Niños or nourishments, distinctly stand out in the beach width record and, along with long-term trends (e.g., Torrey Pines) will be the main determinants for establishing a monitoring approach and associated triggers. In particular, El

Niño events have the potential to undo the benefits of nourishment efforts, essentially "resetting" the beach to pre-nourishment conditions. Therefore, the frequency and duration of future El Nino events are important to consider when establishing triggers.

I considered average conditions over 3 to 5 kilometers sections of the beach. Further work is needed to assess beach width change for smaller sections and in this case, the indicator time series will be noisier. Annual sampling with surveys at 1 kilometer spacing, like that of SANDAG's monitoring program, may be sufficient for a monitoring program, with spring being the more preferable time of year to sample.

Understanding the natural variability of beach width will be key to future beach and coastal management as it informs the state of the beach and how it may be evolving. This will allow cities to proactively adapt its beach management practices to preserve and protect the region's beaches. Even with routine annual monitoring, cities may be able to efficiently track the state of the beach and establish triggers that inform when new adaptation or protection measures need to be adopted.

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