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SANTA CRUZ

EVALUATION OF LONG-TERM AND STORM EVENT CHANGES TO THE BEACHES OF THE SANTA BARBARA SANDSHED

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By

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EVALUATION OF LONG-TERM AND STORM EVENT CHANGES TO THE BEACHES OF THE SANTA BARBARA SANDSHED

ABSTRACT

This research analyzed a 70-year record of historic beach width changes and shoreline position along 70 kilometers of the Santa Barbara and Ventura county coastlines to assess whether beaches were systematically narrowing in response to a reduction in sediment supply caused by natural factors or human alterations. Using a combination of rectified historic aerial photos and topographic lidar data sets, two shoreline reference features were used to identify the dry sand portion of the beaches. With two reference features, both shoreline change rates and beach width changes were calculated and compared. This beach width methodology provided additional information to more traditional shoreline change analyses on beach response, sand volumes, and human alterations.

Results demonstrated that beaches could be divided into two segments determined by the location relative to the Santa Barbara Harbor. Beaches updrift (northwest) of the harbor were found to oscillate with maximum widths measured during the negative Pacific Decadal Oscillation phase while minimum beach widths were measured following major El Niño events. Downdrift of the harbor (southeast) no such patterns were identified, indicating that harbor dredging and bypasses controlled beach widths. Littoral drift rates both updrift and downdrift were found to be about 1.7 km/year.

Pulses of sand appear to move coherently through the littoral system and could be seen in transit on stable beaches that had a wide minimum beach width. Beaches between the stable beaches showed little signs of large volumes of sand passing suggesting that longshore transport in these reaches occurs offshore.

Beach width responses to large El Niños match long-term shoreline change patterns of shoreline reorientation indicating that El Niños play a major role in large-scale, long-term coastal evolution. El Niños were also shown to have significant impacts on nearly all aspects of sandy beach ecosystems, demonstrating the importance of physical process considerations in ecological studies.

While the long-term beach width changes did not identify any systematic long term narrowing attributable to sediment supply reductions, analyses revealed a pattern of beach narrowing resulting from shoreline armoring, illustrating passive erosion and placement loss effects. A sandshed concept linking watershed and coastal processes to maintain beaches for their economic, ecological, and hazard protection potential has significant implications for the management of our coasts at a variety of scales.

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John Marra, a friend, mentor, and co-author was crucial in discussions on Chapter Four, Sandshed Management (mahalo!). I hope that the concept can communicate the importance of our beaches to a broader audience. Rondi Jean Robison, Markus Mead and Kevin Ranker also deserve mention for inspiring me to breathe life into an idea, and for working tirelessly for our oceans and coasts.

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Chapter 1

BEACH WIDTH AND CLIMATE OSCILLATIONS ALONG ISLA VISTA, SANTA BARBARA, CALIFORNIA

ABSTRACT

Santa Barbara County beaches adjacent to University of California, Santa Barbara (UCSB), and Goleta Beach, eleven miles west of the Santa Barbara harbor, suffered dramatic erosion during the El Niño events of 1982-83 and 1997-98 and never fully recovered. This study analyzed a 70-year record of beach width changes along a nine-kilometer shoreline segment near Isla Vista, California. Results show an oscillation in beach widths as opposed to a long-term narrowing as predicted based on sand supply reductions. The oscillations of beach width relate to different phases of the Pacific Decadal Oscillation (PDO) Index. During positive PDO phases, El Niño-like patterns of increased precipitation and stream flow narrow beaches while during negative and calmer, drier PDO phases, beach widths widen. Results also indicate significant variability in the beach widths along the study area. Parts of the Isla Vista, UCSB, and Goleta Beach shoreline show significant changes in beach widths, the majority of these areas (59%) correspond to shore protection structures or other human alterations. Significant narrowing of beach widths over the 70-year record were observed at 77% of the transects that intersected shore protection structures, primarily because of placement losses.

El Niños play an important role in decreasing beach widths (widths narrow by >50%) with all of the narrowest beaches occurring after the major events of 1982-83 and 1997-98. The 1982-83 El Niño was the key event resulting in the largest beach width changes, especially along Isla Vista, UCSB and Goleta beaches, where beaches have never recovered to pre-1982-83 levels. Beach widths following the 1997-98 El Niño did recover to post –1982-83 levels. The volume of sand removed from the beaches of the study area during the 1982-83 event was estimated to be around 385,000 m^3. From 1993-1995, sand volumes dredged annually from Santa Barbara harbor show a 74% increase above long-term averages (230,000 m^3/yr) which match the volume loss at UCSB and Goleta Beach, providing some evidence of a 1.7-km/yr (1 mi/yr) alongshore transport rate of littoral sands. Including beach width measurements in shoreline change assessments provide additional information on beach processes, storm response, and human alterations that can aid coastal management decisions.

Keywords: El Niño, coastal erosion, shoreline change, Goleta Beach, Santa Barbara Channel, University of California, Santa Barbara, Coal Oil Point, Ellwood, shore protection structures, placement loss, Pacific Decadal Oscillation.

INTRODUCTION

The Santa Barbara Littoral Cell has experienced a 40% reduction in sand supply since 1920 due to dam construction on the four major rivers draining to the cell and 14-km of coastal armoring (Willis and Griggs, 2003, Runyan and Griggs 2003) (Figure 1). With such reductions in sand supply , a corresponding decline in the amount of sand on the beaches is expected. In addition, a relatively steady 70-yr average of 230,000 m^3/yr of sand dredged from the Santa Barbara Harbor, shows no decline of sediment supply with time (Patsch 2005, Runyan and Griggs 2002). With the dominant wave and longshore transport from west to east, one potential impact of an upcoast reduction in sediment supply could be narrower beaches. The objective of this study was to develop a historical record of beach width changes over the last 70 years in order to document which beaches may have systematically narrowed, which have oscillated but not undergone net change, and those which may have widened.

The narrow, south-facing beaches of the Isla Vista coast adjacent to University of California, Santa Barbara (UCSB), are partially sheltered from large storm events by Point Conception to the northwest, and the Channel Islands to the south (Figure 1). During the El Niño events of 1982-83 and 1997-98, storm waves eroded Isla Vista and Goleta beaches, threatening homes and public facilities at a county park. Continuing erosion led to a stakeholder process examining two erosion management alternatives – armoring and a form of “managed retreat”. Portions of this research were presented during these stakeholder/decision-making processes to provide a regional perspective of the historic beach changes.

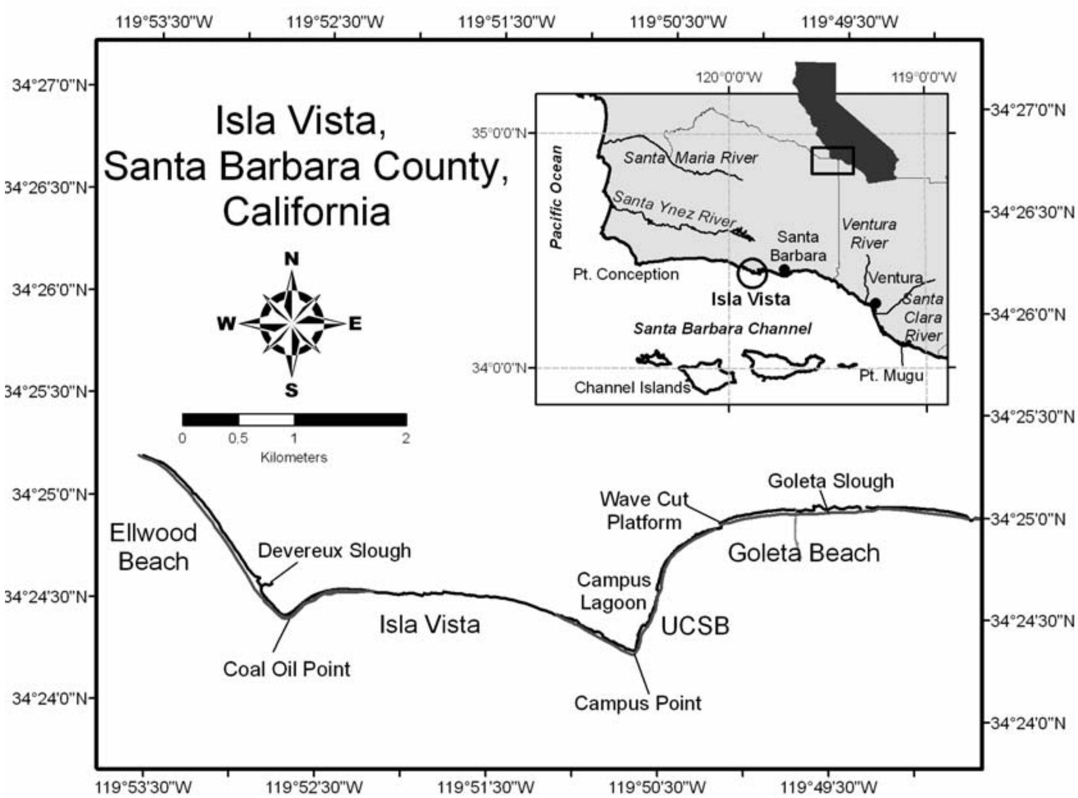

Figure 1: Isla Vista is located in the Santa Barbara littoral cell in southern California. This coastline has been divided into four sections based on the shoreline orientation – Ellwood, Isla Vista, UCSB, and Goleta Beach. The dominant longshore sediment transport moves from west to east.

Many shoreline studies focus on the migration of single reference features, often Mean High Water, or a High Water Line (see Boak and Turner, 2005 for a recent review). The evaluation of two shoreline reference features and beach widths enable a temporal assessment of recreational beaches important to economic evaluations (King

2001), beach rotations (Ranasinghe et. al 2004), and beach and nearshore ecology (Elwany and Flick 1996, Hubbard and Dugan 2003), although such discussions are beyond the scope of this paper. A beach width methodology provides more data for use in the estimation of beach volumes, as well as in the impacts of various backshore types including bluff, dune, and human-altered backshores (fill, riprap, or seawalls) (Willis 2002, Reid, 2004). This paper utilizes beach widths to assess the reductions in sediment supply and hypothesized narrowing of the beaches, as well as examining the impact of human alterations to the shoreline.

The study area was divided into four segments based on distinct shoreline orientation (Figure 1). The segment from Ellwood to Coal Oil Point (2.5 km) is a dune-backed shoreline that faces southwest into the dominant wind and wave direction. The Isla Vista segment (3.3 km) stretches from Coal Oil Point to Campus Point, faces primarily south and is backed by bluffs composed of Sisquoc shale with a thin lens of sand on top of a bedrock platform. The UCSB segment (1.5km) faces southeast and stretches from Campus Point to a wave-cut platform to the east. This segment is backed primarily by a Sisquoc/Monterey shale bluff with several portions backed by riprap. Goleta Beach (2.3 km) faces south and stretches from the wave cut platform in the west to a rocky outcrop on the eastern side of the Goleta Slough. This shoreline used to be a sandspit, separating Goleta Slough from the Pacific Ocean, but was stabilized with fill in the mid-1940s, and has been armored with riprap at various locations through what is now Goleta Beach County Park (Moffatt and Nichol 2002).

Climate Oscillations

Large-scale meteorological conditions that control the climate throughout the Pacific Basin have shifted on a 20+year time cycle, an oscillation called the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997). The PDO is an index for sea surface temperatures in the Pacific that affects the intensity of El Niños and La Niñas during the various regimes. A positive PDO (negative PDO) is associated with El Niño-like effects (la Niña-like effects) that increase (decrease) the intensity of the Aleutian Low, and affect precipitation, and streamflow (Mantua et al. 1997, Nigam et al. 1999). Reversals in the PDO occurred in 1925, 1947, and 1977, (Mantua et al. 1997) with debate ongoing about a potential shift in 1999 (Bond et al. 2003).

The Pacific North American (PNA) climate pattern is another multi-decadal climate oscillation based on atmospheric pressure differences between the North American continent and the Pacific Ocean (Wallace and Gutzler 1981). Inman and Jenkins (1999) examined water and sediment discharge along twenty coastal streams in Central and Southern California and found a strong relation with the PNA "wet phases" (1969 to present) with high sediment fluxes to the coast from episodic storm events, while a "dry phase" -low sediment flux period existed from 1944-1969. Effects of this climate oscillation are diverse and widespread and have been observed in changes in salmon production (Mantua et al. 1997) and along beaches in Maui, Hawaii (Rooney and Fletcher 2005).

METHODS

Historic Beach Changes

Mapping shorelines and conducting beach change analyses is difficult due to the complex natural dynamics of the ocean-land interface that operate on a variety of time and space scales, as well as the differing reference features used by individual investigators (Crowell *et al.* 1991; Moore 2000; Boak and Turner 2005). Time scales include storm events, changing tide levels, seasonal fluctuations, intra-annual variability, decadal oscillations, and long-term sea level rise. In order to assess historic changes, it is necessary to compile as long of an historic record as possible to average out storm and tidal effects, and compare photos from the same season to avoid incorporating seasonal fluctuations (Anders and Byrnes 1991, Morton and Speed 1998).

Historical aerial photographs provide one of the best data sources for long-term shoreline and beach width changes. For this study, 16 different sets of vertical air photos were obtained for the period from 1938 to 2003 (Table 1). Photographs selected for this study were taken during the calmer season (summer to fall) to ensure that beaches were near a maximum width. To minimize errors, all photos were georeferenced to field collected survey grade GPS coordinates to reduce photo distortions ((Moore 2000, Morton *et al.* 2004, Hapke 2004). For each image, two shoreline reference features were digitized - the wet/dry line or High Water Line

(HWL) and the back beach (Figure 2). The back beach feature was usually either the toe of the bluff or dune. The beach width is the distance between the wet/dry line and the back beach feature, generally the dry sand portion of the beach at the time of the photo. Beach widths for all imagery were measured along the same 50-meter transects using the USGS Digital Shoreline Analysis System (DSAS)(Thieler, *et al*. 2003). Shoreline change was evaluated in addition to beach widths using DSAS (Thieler *et al*. 2003), but error bars on the shoreline changes were near the widths of these narrow beaches, and are generally not reported except in the discussion of Ellwood Beach where the changes were larger than the errors.

Year	Date	Scale	Dpi	Error (m)	Tide (m) MLLW	Tidal Level Adjustment (m)	Photo Source
1938	?	1:24000	600	9.1	-	-	UCSB – Map Imagery Lab
1943	9/21/43	1:20000	600	9.2	0.9	0m	UCSB – Map Imagery Lab
1947	8/20/47	1:15600	600	9.3	1.6	14m	UCSB – Map Imagery Lab
1959	11/23/59	1:12000	600	8.4	0.9	0m	UCSB – Map Imagery Lab
1966	9/23/66	1:12000	600	8.4	0.9	0m	UCSB – Map Imagery Lab
1969	10/30/69	1:12000	600	8.3	1.3	8m	UCSB – Map Imagery Lab
1971	6/1/71	1:12000	600	8.2	0.6	(-) 6m	UCSB – Map Imagery Lab
1973	8/23/73	1:24000	600	8.1	0.9	0m	UCSB – Map Imagery Lab
1975	7/29/75	1:24000	600	7.2	1.2	6m	UCSB – Map Imagery Lab
1983	10/30/83	1:24000	1200	6.1	1.4	8m	Pacific Western Aerials
1986	10/31/86	1:24000	1200	6.5	0.8	(-) 2m	Pacific Western Aerials
1989	5/22/89	1:24000	1200	6.4	0.4	(-) 10m	Pacific Western Aerials
1994	9/9/94	1:24000	600	5.0	1.0	2m	USGS
1997	6/6/97	1:24000	600	5.8	1.1	4m	Pacific Western Aerials
2001	9/25/01	1:12000	1200	6.3	1.0	2m	California Coastal Commission
2003	6/25/03	1:6000	1200	5.4	0.9	0m	Pacific Western Aerials

Table 1: Specifications of aerial photography and errors associated with the rectification and tidal water level adjustment based on tide level at time of photo.

Errors inherent in air photo interpretation can be broken down into 1) source error, 2) interpretation error, and 3) short-term natural variability errors (Morton and Speed 1998). Source error results from photo distortion, scale, and scanning errors (Moore 2000, Hapke 2004). Interpretation errors come from difficulty in locating shoreline reference features. Short-term variability errors arise from seasonal changes in beach profile and variations in water levels and wave run-up elevations that change the location of the shoreline reference features (Morton and Speed 1998, Ruggiero *et al*; 2001, 2003)

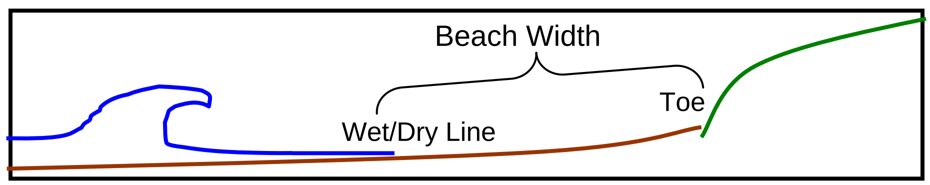

Figure 2: Measurement of beach width is from the wet/dry tonal contrast to the toe of the bluff or dune

Errors associated with this study were calculated using an additive method combining the three types of errors (Table 1). Source error was measured as a combination of the scale and type of the source imagery, (i.e. either a contact print, diapositive, or negative); the digital conversion method that determines the pixel size (dependant on type of scanner and scanning resolution); and the rectification procedure using GPS points for ground control that generated a total RMS for the rectification solution. Interpretation errors for early photography (pre-1970) were assumed to be approximately 5 m based on estimates from other authors (Moore 2000). For photography taken after 1970, historic oblique images found at www.californiacoastline.org facilitated the identification of reference features and errors were found to be +/- 2 m based on repeated reference line digitizing. Finally, the short-term variability associated with the movement of the wet/dry line was minimized based on the application of a tide level adjustment discussed below. The location of the shoreline reference features and spatial errors associated with shoreline change analysis are, at most, +/- 9.3 m for the earlier 1938 photography. More recent photography scanned at a higher resolution provided lower spatial errors on the order of +/- 7m (Table 1). Unlike the shoreline change analysis that depends on different images, the errors in beach width measurements are spatially independent since both reference features can be seen in the individual images. Beach width errors are +/- 5m and arise from reference feature identification and water level adjustments.

Given the short-term variability discussed above, tidal level corrections were made to the HWL shorelines using the water level data from Santa Barbara Harbor at the time of the historic photo. These corrections translated the water level at the time of the photo onto an average beach slope estimated from historic profiles and from the 1997 LIDAR for each shoreline segment. A tidal elevation of 0.9 m MLLW was determined to require the least amount of water level corrections to all photographs. Water level corrections to proxy based shoreline reference features were based on the tide level portion of the total water level method discussed in Ruggiero et al. (2003), and Moore *et al.* (2005) (Table 1). Due to the typical low energy waves found in the Santa Barbara Channel during the summer and fall, and the lack of hindcast wave data for most of the photography, a wave run-up adjustment was not included in the proxy based shoreline correction.

For the 1997 and 1998 dates, LIDAR–ATM data were utilized to provide accurate topographic information about the beach (Sallenger *et al.* 1999, 2003). The LIDAR data were processed to extract a MHW tidal datum shoreline based on Santa Barbara Harbor records (1.4 m NAVD88) and a 0.9 m (NAVD88) shoreline based on aerial photography tide levels. Beach slopes were extracted along each transect combined with historic beach profiles for use in the water level corrections to estimate sand volumes from beach area. The LIDAR images were then examined in 3D and a backshore reference feature was hand digitized. The 0.9 m shoreline and the backshore reference features were then incorporated into the photo-derived beach width change analysis in an effort to minimize proxy biases resulting from the comparison of HWL and MHW shorelines (Moore *et al*. 2005).

Beach areas were calculated by multiplying the beach width adjusted for tide level at each transect by its 50 m spacing and adding each transect area along a shoreline segment for a total area. For these area calculations, the 1998 beach was not included since the data captured in April showed both a storm and seasonal response and thus were not comparable to other years. The calculation of beach volumes represents the volume of sand found on the subaerial (dry sand) portion of the beach above 0.9 m elevation (NAVD88). Beach volumes were calculated by multiplying the beach area between transects by the average beach slope used in the tide level correction for each segment then summing the products of each transect volume for the shoreline segments.

ANALYSIS AND DISCUSSION

Beach Oscillations

The beaches in this area have varied in width over the 70 years of the study (Figure

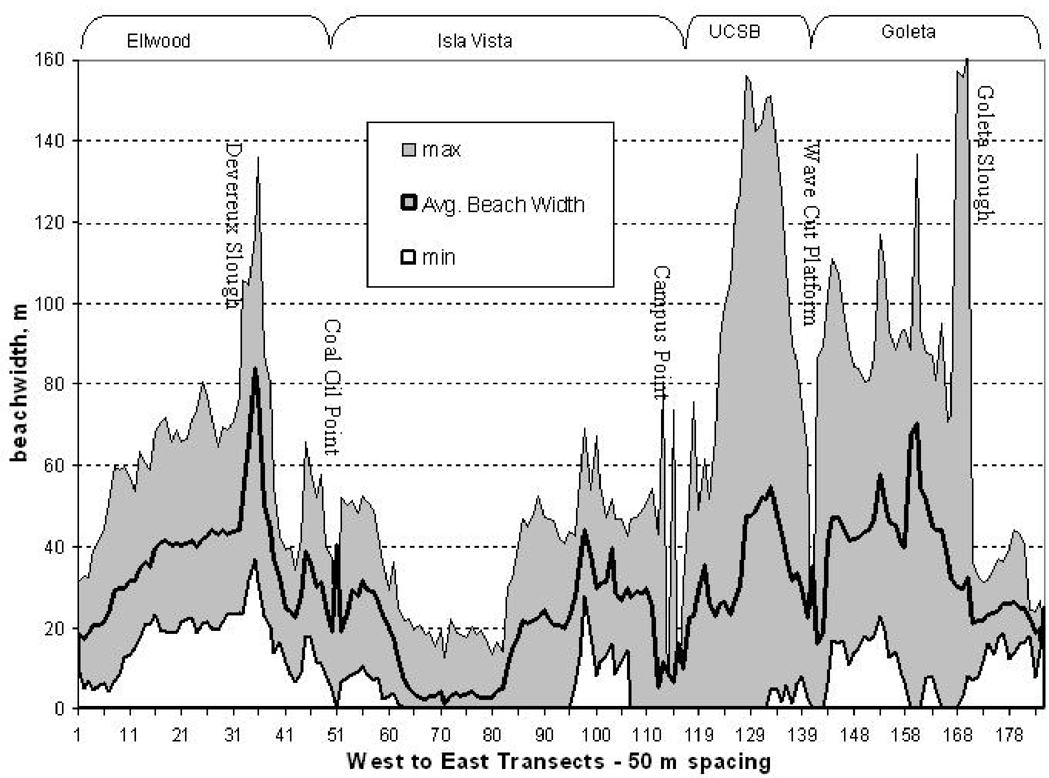

Figure 3: Beach width envelops – the bold line is the average beach width with the gray shading indicating the minimum and maximum throughout the study area for the time period between 1938-2003. The areas of highest variability are found at UCSB and Goleta Beaches, indicating the highest capacity to store sediment. All of the minimum beach widths were measured either in 1983 or 1998 following major El Niño events.

3). The narrowest widths across the study area were measured following either the 1982-83 or 1997-98 El Niños. Despite high longshore transport rates estimated to be between 200,000 m3/yr and 230,000 m3/yr (Moffat and Nichol 2002, Patsch 2005), reaches of shoreline with wide beaches have persisted for over a decade. Overall, variability found across these shoreline segments suggests that the beaches of UCSB and Goleta with higher width variability (0-150 m) may have a higher capacity for sand storage. This variability also suggests that Ellwood with the widest minimum beach widths (~20m) may be the most stable.

Ellwood

This dune-backed stretch of shoreline faces southwest and is subject to the most direct wave energy in the study area. Beach width envelopes along Ellwood range from 35 meters at the west end to 90 meters at the slough inlet (Figures 1, 3), dropping to 15-30 meters around Coal Oil Point. The maximum beach widths have been measured recently in 2001 and 2003, after the 1997-98 El Niño. The smaller ranges in beach widths (~60 m), with a higher minimum beach width (~20 m) suggest that Ellwood is the most stable beach in the study area.

Isla Vista Beach

Turning east around Coal Oil Point toward Isla Vista, the shoreline is oriented east to west and the beach significantly narrows (Figures 1, 3). Isla Vista exhibits the smallest range of beach widths (<20 m) such that during winter, the beach often erodes to bedrock. The first 250 m stretch of shoreline adjacent to Coal Oil Point ranged from 5-50 meters wide, depending largely on the presence of a rip embayment. The beach width from Coal Oil Point to the middle of the Isla Vista segment was widest (~20 meters) in 1938, before much of the coastal development had occurred. Historic oblique photos from 1929 show a narrow beach prior to residential development. The beach widens toward Campus Point to a range of ~20-50 meters with two wider beach segments found at former entrances to the campus lagoon (Figure 1). The maximum widths along this eastern stretch of Isla Vista were found in 1966 and 1969. The beach disappears around Campus Point where historic oblique images show several meters of vertical erosion in the rocks.

UCSB

East of Campus Point and extending to Goleta Beach, the shoreline orientation changes to southeast facing and the beach widths have the highest variability (Figures 1, 3). Inside of Campus Point, the beach ranges from 5-60 meters in width with a maximum width of 75 meters in 1966. Since the 1982-83 El Niño, this section has not been wider than 45 meters. Farther east along UCSB Beach is the largest beach width envelope in the study area, ranging from 20-40 meters in the 1930s and 1940's to a maximum range between 70-150 meters in 1975 (Figure 4A & B). The present beach widths are similar to those measured in the photos taken in the 1930s and 1940s. The 1982-83 El Niño scoured this beach, which remains in the 20-40 meter range. Photographs (Figures 4A and 4B) illustrate the magnitude of the beach width change.

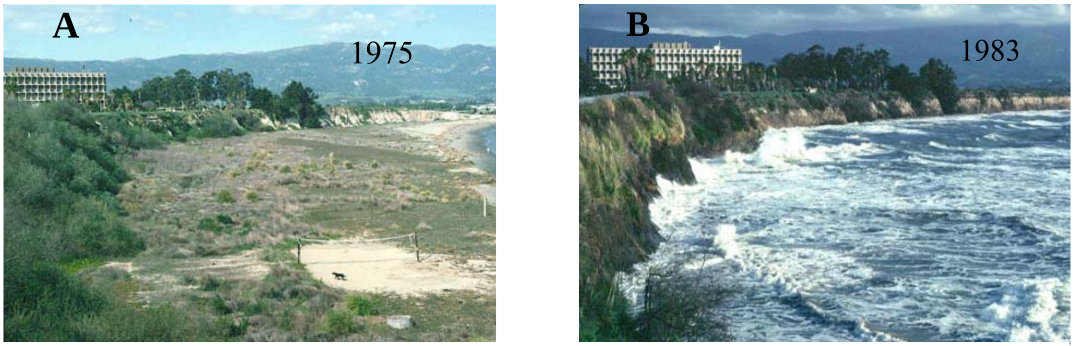

Figure 4A and B. Photos showing 150-meter wide beach at UCSB before the 1982-83 El Niño and waves attacking the cliffs during the 1983 winter.
Photos by Art Sylvester

A wave cut platform lies at the downcoast end of UCSB Beach, and was periodically covered by a sandy beach during the late 1950s into the early 1980s. It has been continuously exposed since the 1982-83 El Niño. The wide variability in this section may indicate a large storage capacity for sand.

Goleta Beach

Goleta Beach has ranged in width from 30-120 meters (Figures 1, 3). During the 1930-40s, the beach was less than 40 meters in width as measured using the most landward back beach reference feature found in the 1943 photographs. In 1945, Goleta Beach was constructed with non-select fill (www.santabarbaraparks.org/goletabeach/history.htm). From the late 1950s to the early 1980s, Goleta Beach accreted to 70-120 meters, with the maximum beach widths occurring in 1975. Since the 1982-83 El Niño, however, the beach has remained on average about 30-40 meters wide, similar to widths measured on photos from the 1930s and 1940s.

The timing and variability associated with beach widths along the shoreline of the study area indicate that there has not been a long-term erosion trend as originally hypothesized based on sediment supply reductions, but rather an oscillation in beach widths. There are several potential explanations for this somewhat unexpected finding. Sand could be transported offshore from the inner shelf, an analysis that was beyond the scope of this study. Another potential explanation is that the distance (~90 km) from the dammed rivers to the study site could mean that we have yet to see the narrowing associated with dam construction due to the lag time in downstream and downcoast impacts.

Significant Beach Changes

Measurements of beach width illustrate wide variability over the 70-yr time period (Figure 3). Since this time period spans pre- and post- shoreline armoring, the measured variability includes effects associated with shoreline armoring or other human alterations. To determine which of these changes were most important, the average beach width at each transect was calculated, along with the standard deviation as a measure of the overall beach variability (Figure 5). Significant changes here are defined as beach width maximums exceeding two standard deviations. Maximum measurements taken from early in the photo record (1938-1959), prior to alterations, indicate a narrowing of the beach, while maximum measurements taken in more recent times (1994-2003) indicate an increase in the beach width. Moving west to east along the shoreline, significant changes to the beach widths are highlighted along Isla Vista, UCSB, Goleta Beach, and at the mouth of Goleta Slough.

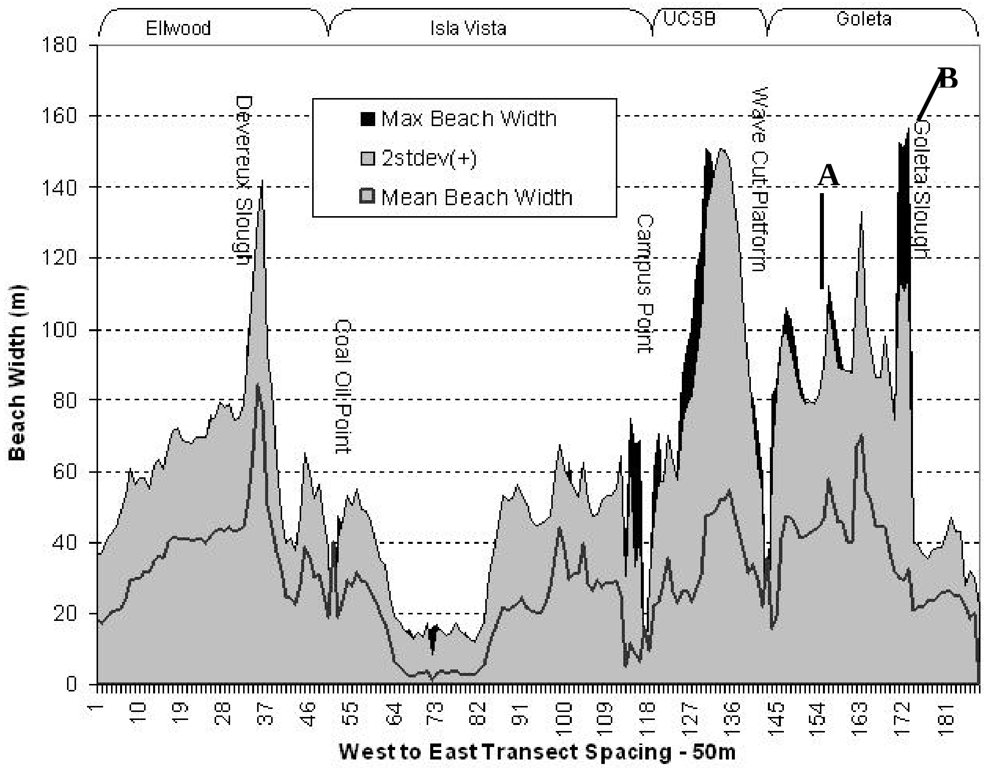

Figure 5: Significant beach width changes – the bold line is the average beach width throughout the study area for the time period between 1938-2003. Maximum beach widths exposed indicate locations of significant beach changes due to either human alterations to the shoreline or a sea cliff backed beach with a history of complete erosion. Examples of significant changes A – Figure 6, B Figure 7

Of the 185 measured transects along 9 km of shoreline, only 22 indicated significant changes to the beach width outside of the error bars. Thirteen of these 22 transects recording significant change (59%) occur along stretches of human-altered shoreline where the beach widths have narrowed. The 9 remaining significant transects occur along stretches of seacliff backed shorelines, where at times the beach has been completely eroded (Figure 4A & B).

Human Impacts

Across the study area, 77% of all transects with an armored backshore showed significant reduction to the beach width in front of them (10 of 13 transects). Along the Isla Vista, UCSB, and Goleta Beach segments, most transects correspond with examples of placement loss (8 of 10) (impoundment) and passive erosion (2 of 10) (beach drowning) where structures were built to protect buildings, restrooms, and parking lots (Griggs 2005) (Figure 5). While all structures on the beach cause some level of placement loss, the vertical seawalls do not show the placement loss due to the accuracy of the data and this loss is usually very small due to the narrow width of most seawalls compared to placement loss from riprap.

One example of placement loss at Goleta Beach occurs along the pier, restaurant facilities and parking lot where riprap was initially placed on the beach in the 1960s and then augmented periodically in response to subsequent erosion events. In 1943, the back beach was at its most inland position with a 50 m - 80 m wide beach in 1943. Park facilities coupled with the riprap narrowed the recreational beach to between 10 m and 20 m by 2003 (Figure 6). The beach just updrift and downdrift of the riprap has maintained a steady beach width of ~45 m.

The most significant change occurs at the mouth of the Goleta Slough. In 1938, an ebb shoal is clearly visible and the maximum beach widths for the shoreline near the slough entrance were measured (Figure 7 - A). In the 1940s, Mescalitan Island

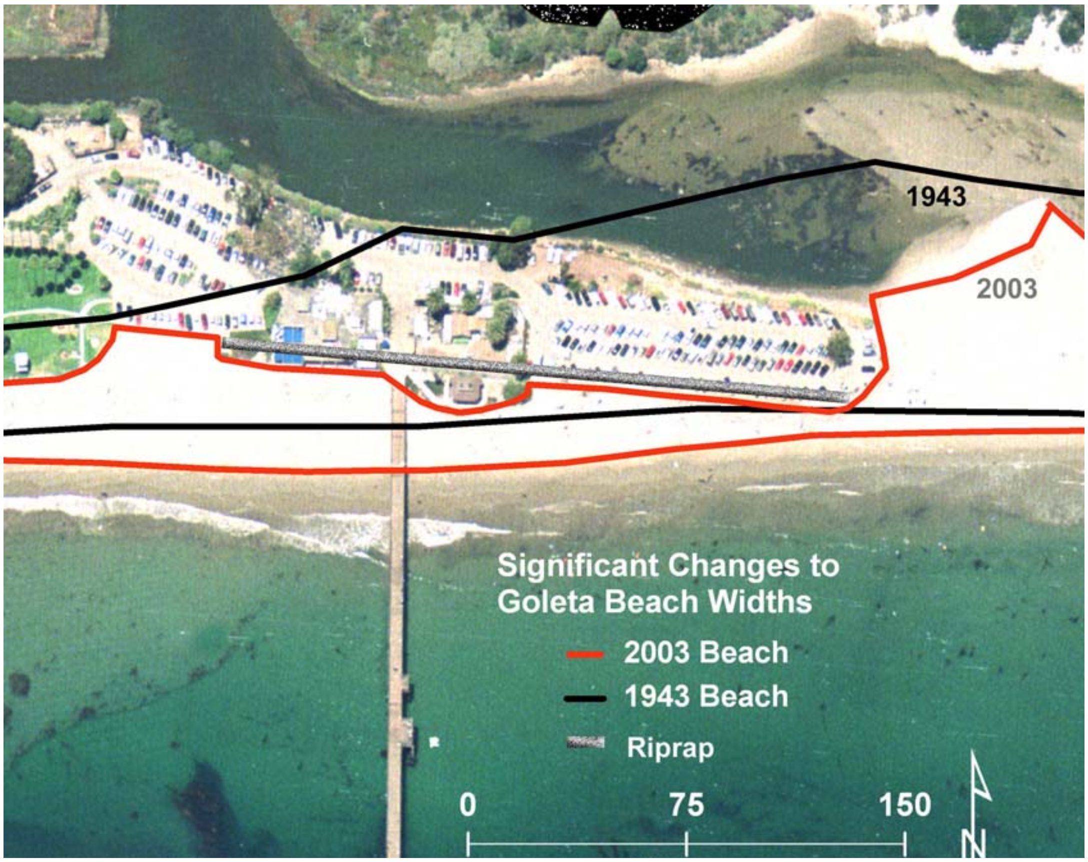

Figure 6: Goleta Beach showing locations of significant change due to placement loss, resulting in a narrowing of the beach width in front of the riprap armoring. 1943 beach widths have been encroached upon by riprap and the parking lot as evidenced by the 2003 beach and photo. The extent of the riprap along the shoreline corresponds spatially with the extent of significant changes**.**

(Figure 7 –B) was flattened to fill Goleta Slough and create the Santa Barbara Airport; since then the ebb shoal and beach widths have not been as large. A study on changes to the saltmarsh vegetation shows an increase in freshwater vegetation types lower in Goleta Slough as a result of the changes to the slough hydrology and a reduction in the tidal energy (Onuf 1983). The filling of the slough/saltmarsh for the airport may have reduced the tidal prism, which would have reduced the ebb current capacity to transport sediment out of Goleta Slough.

Figure 7: Entrance to Goleta slough in 1938 (A). Note the island (B) in the top center of the photo that was bulldozed to provide the fill for the Santa Barbara Airport. The large delta visible on the right side (A) of the photo has not been seen since the construction of the airport in the early 1940's.

Unrectified image courtesy of UCSB Map and Imagery Lab**.**

Figure 6 shows a benefit to looking at beach width changes when assessing coastal hazards. An end point change rate analysis using either of the shoreline reference features would show that the beach accreted between 1943 and 2001. The beach width polygons show the encroachment of facilities and shore protection structures onto the beach, reducing the beach width as opposed to a shoreline accretion signal that implies a movement of the shoreline seaward.

Total Beach Area

Beach area for an individual year compared with adjacent years provides some evidence that the seasonal signal has been removed from the data (Figure 8). Prior to the 1982-83 El Niño, beach areas and widths were similar to adjacent years, with the total 9-km beach area averaging around 380,000 m^2 (Figure 8). Following the 1982-83 event, the beach area was reduced by 120,000 m^2 to ~250,000 m^2. The impact of both the 1982-83 and 1997-98 El Niño events reduced the beach area by over half. Beach widths before the 1982-83 El Niño averaged about 48 m while beach widths following 1983 were about 20 m with each segment responding differently. Beach widths before the 1997-98 El Niño averaged about 30 m while beach widths following 1998 were only about 11 m. These post-storm beach widths were measured using LIDAR collected in April, however, which included a seasonal signal. Immediately following both El Niño events there was a period of initial beach recovery, so that by 1986 and 2001 the beaches had recovered about 75% of their previous area. Recovery following the 1997-98 El Niño was observable to post-1982-83 levels. The 1982-83 El Niño appears to have been a key erosion “event”, since beaches have not recovered to pre-1983 beach widths.

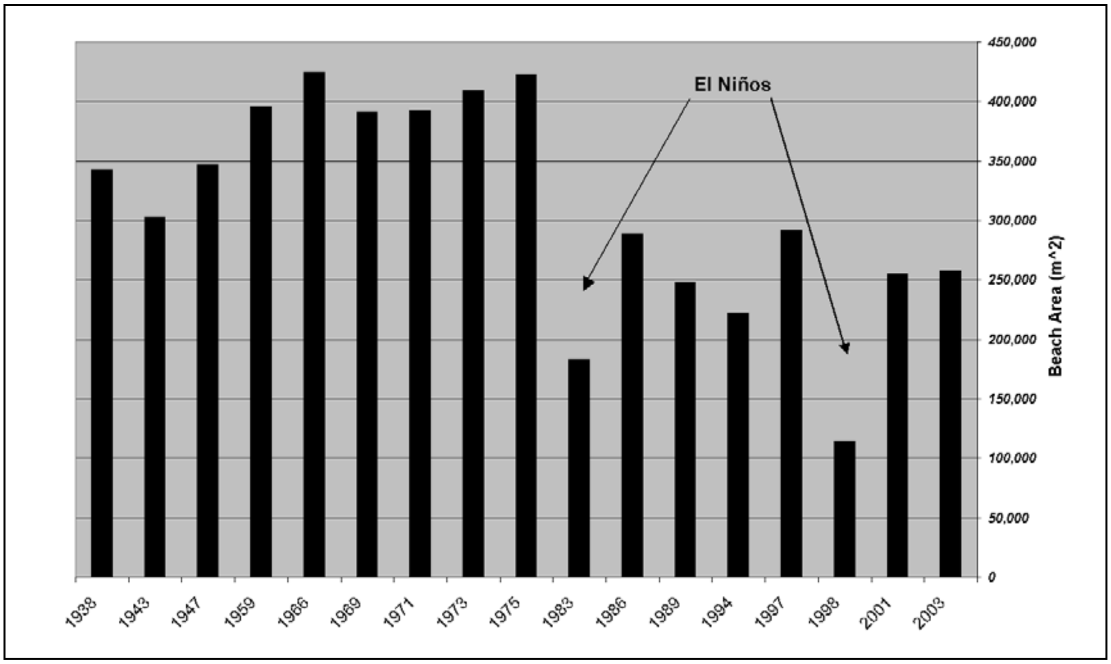

Figure 8: Beach area calculated as the sum of the beach widths for that year times the 50 m transect spacing. Low or narrow years follow the major El Niño events, 1982-83 and 1997-98. Prior to the 1982-83 El Niño, beach area averaged about 380,000 m^2 while beach areas in subsequent years have averaged about 230,000 m^2. Note the 1997 and 1998 dates are derived from LIDAR.

Individual Shoreline Segments

Each shoreline segment shows oscillations in beach area (Figure 9). Periods when the beach was narrowest at Ellwood correspond to the widest beaches at Goleta Beach and UCSB (1966-1975). Isla Vista, UCSB, and Goleta beaches share similar patterns of erosion following the 1982-83 El Niño, when beaches along these stretches were narrowed dramatically (>50%) and have not recovered to pre-1982-83 widths.

Ellwood

In Ellwood, shoreline segments maintain an average area of 100,000 m^2 or an average beach width of about 40 meters. The smallest beach areas measured for several years occurred from 1966 to 1975. The largest beach areas, surprisingly, occurred following the 1997-98 El Niño. After each of the major El Niños, Ellwood maintained a significant beach, often recovering faster than the other shoreline segments.

There are distinct differences between the response of Ellwood and the other shoreline segments during both the storm response and recovery to El Niño storm events and to the longer PDO cycles. While other segments exhibit dramatic changes (>50% decline in width), Ellwood maintains a relatively constant beach width (Figure 9 and10). This stability may be related to the natural dune backshore that can erode in storm events and supply sand to the beach. Between 1966 and 1975, the beach width at Ellwood narrowed as a result of the growth of vegetation and the progradation of the backshore. Immediately following the 1982-83 El Niño, both of the Ellwood shoreline reference features eroded an average of 25 m while the beach width remained constant. The backshore remained at a similar eroded position while the wet/dry line moved seaward, explaining the large beach width observed in 1986. This illustrates the need to understand both the beach width and the shoreline change when addressing coastal hazards, especially in shorelines with a dune backshore.

Isla Vista

This shoreline segment experienced significant erosion over the 70-year time period with the largest changes in beach widths occurring after the 1982-83 El Niño. In 1938, the area of the beach was about 80,000 m^2 with an average beach width of 25 meters. In 2003, the beach narrowed to about 40,000 m^2 with an average beach width of 12 meters.

UCSB

The area of beach within the UCSB shoreline segment increased from 1938 until the late 1970s. The largest beach area occurred between 1966-1975 and was

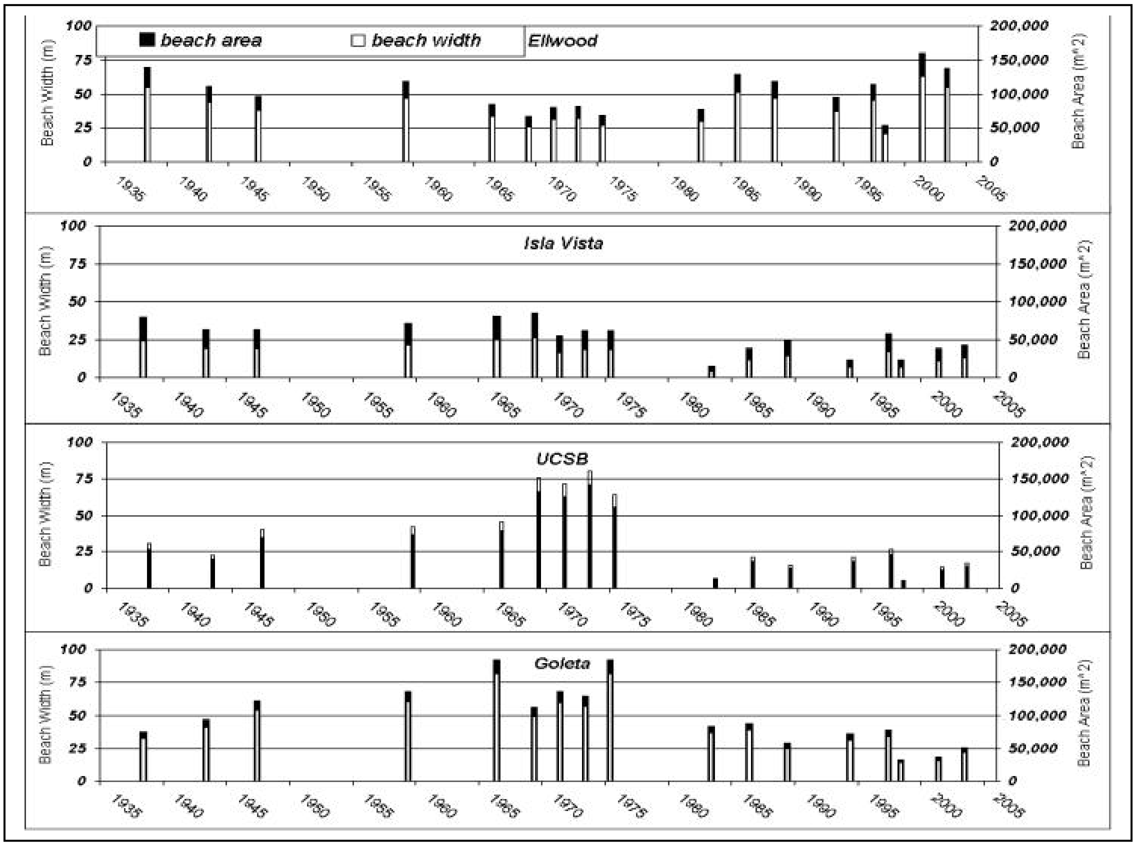

Figure 9: Time record of beach area for each shoreline segment. Each segment has a different orientation and wave exposure. Ellwood remains the most stable throughout the time period with IV, UCSB, and Goleta sharing a similar beach erosion trend following the 1982-83 El Niño. Note the 1997 and 1998 dates are derived from LIDAR.

approximately 140,000 m^2. Following the 1982-83 El Niño, the beach area was significantly reduced to less than 50,000 m^2 with an average width of about 4 meters (Figures 4A and B).

Goleta Beach

The Goleta Beach shoreline segment follows a similar pattern as UCSB with the 1982-83 El Niño event reducing the beach area by over 100,000 m^2 from an average width of over 80 meters to an average width of about 35 meters. Following the 1997-98 El Niño, Goleta again lost over half of its average beach width from 34 meters down to 12 meters; about 35,000 m^2 of beach area was lost.

Sediment Transport

Considering the strong unidirectional west to east alongshore transport, the sand eroded from UCSB and Goleta Beaches during the 1982-83 El Niño should have been gradually transported downdrift some 19 km to the east and recorded in the Santa Barbara Harbor dredge records (Runyan and Griggs 2002). The beach areas along Goleta and UCSB were converted to beach volumes (1975 = ~590,000 m^3 (168 m^3/m); and 1983 = ~205,000 m^3 (59 m^3/m)). We would expect a change in the volume of sand between the two years (~385,000 m^3) to be eventually recorded in the dredge volumes at the harbor. The dredge records show a large increase (74%) between 1993-1995 when the average annual volume removed was 385,000 m^3/yr, significantly larger than the long-term average of 230,000 m^3/yr. The sand volume lost from the study area and the increase in sand volumes dredged at the harbor are of similar magnitudes.

The dredge volume increase 11 years after the 1982-83 El Niño provides some evidence that the sediment eroded from Goleta and UCSB Beaches during the 1982-83 El Niño was transported at about ~1.7 km/year (~1 mi/yr), since the harbor is 19 km downdrift from the study area beaches. This matches the general alongshore migration rate estimates of other authors found in the Danish North Sea (Bruun 1955) and elsewhere in the Santa Barbara Channel (Bailard 1982, Wiegel 2002). While a better understanding of transport rates may lead to predictions of erosion or accretion along certain beaches, the behavior of the sand as it moves downcoast, either along the beach, in a sand wave, or offshore to nearshore bars, requires additional research.

Climate Oscillations

Between 1946 and 1978, the coast of California was in a negative phase of the PDO, a 25+ year time period during which calmer, drier La Niña-like conditions prevailed (Figure 10) (Mantua *et al*. 1997). During this era, the beaches of the study area reached their maximum size ~405,000 m^2. From 1978 to 1998, a positive PDO with El Niño-like conditions (higher wave energy and more rainfall), dominated the climate and the total beach area averaged only about 225,000 m^2 (Figure 9). The correlation of beach widths to the different phases of the PDO suggests a climate connection (Figure 11).

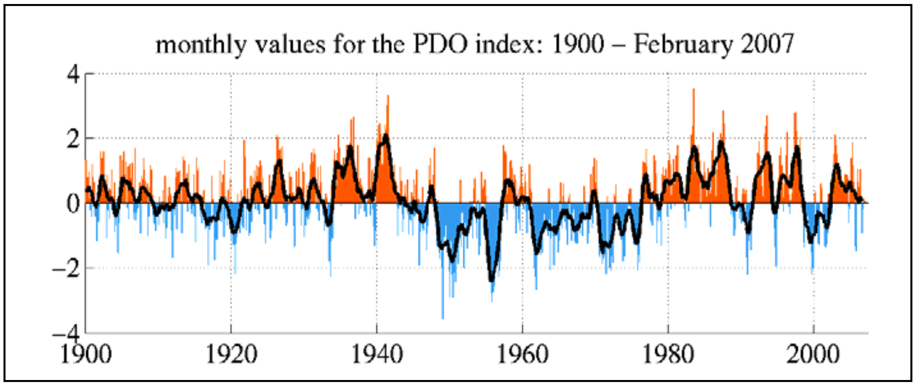

Figure 10: Pacific Decadal Oscillation Index 1900-2007 from University of Washington. http://jisao.washington.edu/pdo/

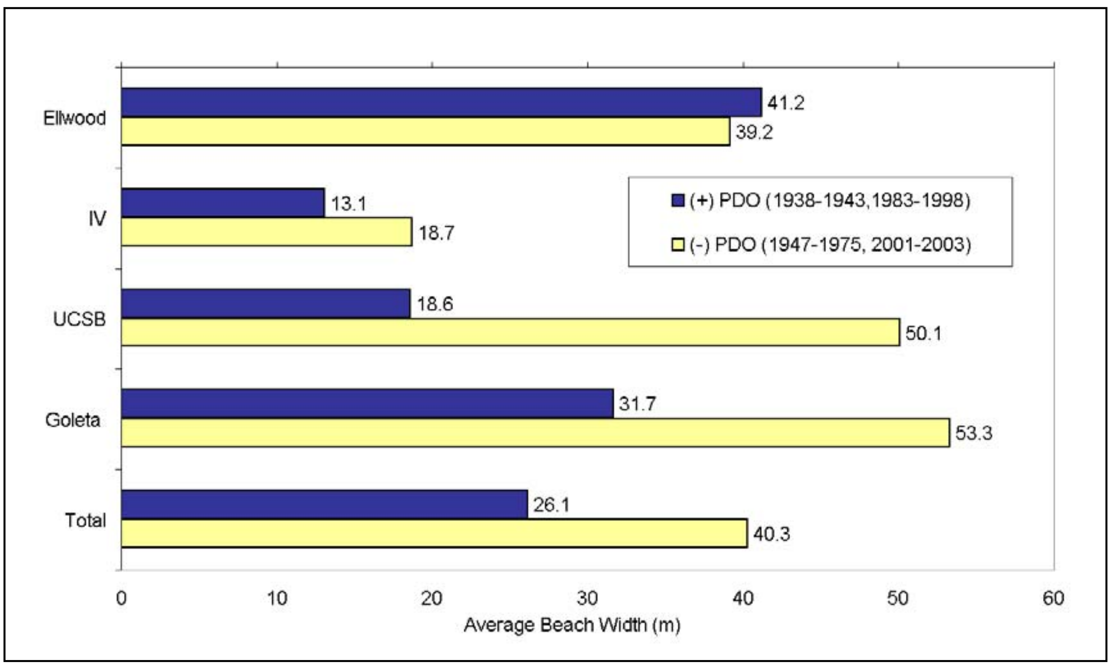

Figure 11: Average beach widths grouped into PDO time periods. Figure legend shows the dates of photography used in each phase.

relatively stable throughout the time periods with slightly wider beaches during negative PDO phase [El Niño dominated phase] from 1938-1943 and 1983-1998. Figure 11 does not consider the shoreline change at Ellwood, which shows a stable beach in both climate regimes. UCSB has experienced the most extreme fluctuations in beach width between climate phases (63%).

Inman and Jenkins (1999) report on multi-decadal sediment fluxes with significant increases during the wet phases of the PNA climate (1969-1998). Sediment fluxes for the Transverse Ranges, where the present study is set, were found to be an order of magnitude higher than other basins due to their geologic composition. While Inman and Jenkins include the four major rivers in the Santa Barbara littoral cell, the updrift rivers - Santa Maria andSanta Ynez, and downdrift rivers - Ventura, and Santa Clara- the consistency in their findings between these rivers suggests that the smaller coastal basins of the Transverse Ranges draining into the Santa Barbara Channel experienced similar periodicities in sediment flux. Although sediment fluxes reported by Inman and Jenkins (1999) include all grain size fractions, presumably an increase in sediment fluxes during a wet phase would lead to an increase in sand size material compatible with existing beach sands, and thus widen the beaches.

However, our findings show that the beaches of this area show signs of increasing in width as early as 1959 and 1966 (Figure 8, 9) prior to the onset of the PNA “wet phase”. By using photos from the PNA “wet phase” (1969-1998) based on time periods used by Inman and Jenkins (1999), there is a weaker beach width/climate relationship than when photos are grouped based on the wet PDO period which begins after 1978 (Figure 10). More importantly, despite an increase in precipitation and sediment flux during the positive PDO [“wet phase” PNA], beaches in this study area narrow.

While this beach width correlation with the PDO phases suggests that precipitation and sediment fluxes are not directly related to beach widths, the robustness of the tests is limited by the study period. With a 70-yr record, only one complete PDO cycle has been observed. One possible explanation could be that the increase sediment flux results in a higher occurrence of hyperpycnal flows that could transport sand sized sediments onto the shelf and out of the littoral zone (Warrick and Milliman 2003). Future work is needed to analyze more historical data - to examine the effects of PDO on swell direction and other oceanographic forcing that may affect the beaches.

CONCLUSIONS

This study presents a 70-yr analysis of beach width changes, along the Santa Barbara County shoreline from Ellwood Beach to Goleta Beach in the Santa Barbara Littoral Cell. Present day beach widths across the study area are similar in width to beaches in the 1930s and 1940s, but the widths show an oscillating pattern as opposed to a long-term narrowing of the beaches as predicted based on reductions in sand supply primarily from dam construction. The oscillating beach width pattern along Isla Vista, UCSB, and Goleta segments appears related to the PDO with the narrowest (widest) beaches occurring during the positive (negative) phase of the PDO. This is counter intuitive since Inman and Jenkins (1999) found a strong increase in precipitation and sediment flux during the positive PDO [“wet phase” PNA]; we find that this increased sediment flux did not widen the beaches, at least initially. However this 70-yr beach width record only captures one complete PDO cycle, so additional historical data is needed to assess the strength of this relationship as well as identify any causative mechanisms.

Beach width data show that these beaches vary widely, with UCSB and Goleta the most variable implying that they have the highest capacity to store sand. Ellwood remained the most stable throughout the 70-year time period with the widest minimum width (~20 m) and lowest variability (~60 m). The timing of narrow beaches at Ellwood during the 1950s and 1960s corresponds with wide beaches along the remainder of the study area, and is largely related to the progradation of the backbeach reference feature prior to the 1982-83 El Niño. This illustrates the need to understand both the beach width and the shoreline change when addressing shoreline change, especially in shorelines with a dune backshore.

El Niños have played an important role in affecting the widths of the beaches along this stretch of shoreline. While all of the shoreline segments experienced their narrowest beach widths following the El Niños of 1982-83 and 1997-98, Ellwood was the most stable following the El Niño events, due to the 25 m of dune erosion that supplied sand, enabling the backshore and beach width to migrate inland.

Following the 1982-83 El Niño event, 150,000 m^2 of beach area was lost across the study area, primarily from UCSB and Goleta Beaches. The 1982-83 El Niño appears to have been a critical storm event over the 70-yr time period because the beaches have never recovered to pre- event widths. Beach widths following the 1997-98 El Niño did recover to post –1982-83 levels.

During the 1982-83 event, about 385,000 m^3 of sand was removed from the beaches of UCSB and Goleta Beaches. A significant increase (74%) occurred in the Santa Barbara Harbor dredge records from 1993-1995 when the average dredge volumes (385,000 m^3/yr) were 67% greater than average long-term dredge volumes of 230,000 m^3/yr. The timing and magnitude of increased sand volumes in the harbor dredge records provides some evidence that sand eroded from Goleta and UCSB Beaches was transported downcoast to the harbor at about ~1.7 km/year (~1 mi/yr). This transport rate, given the distance between the nearest major upcoast river (~90 km) and the study area, may partially explain the lack of evidence for a long-term narrowing in beach widths due to dam construction on updrift rivers.

The methodology of measuring beach width enables an examination of important changes to the shoreline by comparing maximum beach widths with the observed variability. Of the 22 transects that exhibited significant narrowing, 59% could be attributed to human alterations. The remainder of the changes occurred along cliff-backed segments of shoreline that have experienced complete erosion of the beach. Significant beach narrowing occurred at 77% of the transects (10 of 13) in front of shore protection structures and was caused primarily by placement loss resulting in a loss of recreational beach. This placement loss was observed at several locations along UCSB and Goleta Beaches. We also identify a significant narrowing of the beaches near Goleta Slough, which we suggest is caused by reduction of the tidal prism due to historic slough alterations.

Future work is needed to determine how pulses of sand move downdrift, whether along the beach or in nearshore bars, and the potential role of hyperpycnal flows in transporting sand across the littoral zone to offshore areas. Additional research examining the PDO and the effect on rainfall, wave heights and direction, and other oceanographic factors is needed to determine what mechanisms control long-term beach widths. While this study is focused on a nine-kilometer stretch of coastline, the findings have implications for other coastal management issues in the Santa Barbara Channel as well as locations with small long term erosion rates punctuated by episodic erosion events.

ACKNOWLEDGEMENTS

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Chapter Two

PHYSICAL AND ECOLOGICAL RESPONSE OF SANDY BEACHES TO THE 1997-98 EL NIÑO

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ABSTRACT

El Niños play a major role in shaping the southern California coastline and its ecology. El Niño processes increase sea surface temperatures, elevate water levels and wave heights, alter wave directions, and increase precipitation. These processes also affect upwelling intensities, nutrient concentrations, and productivities. El Niño conditions enhance coastal erosion impacts affecting not only oceanfront property owners and recreational users, but also habitats and species that depend on the coast. This paper examines the physical and ecological responses to and recovery from the extreme 1997-98 El Niño along Isla Vista, Santa Barbara County, California, a 10-km stretch of south facing coastline with unidirectional longshore sediment transport.

* Primary author revisited original data and research previously published in Dugan & Hubbard 2003.

Our analyses of the impacts of the 1997-98 El Niño combined topographic lidar data with physical measurements and biological surveys to quantify shoreline, beach width, and volume changes and assess biological responses. We quantify significant changes to the shoreline and short-term reduction in beach widths (>60%) and sand volumes (~80%) across the study area. Most of these changes appear related to the back beach type and shoreline orientation. Bluff-backed shorelines lost a greater percentage of the beach volume than dune-backed beaches. Four major erosion hotspots were identified consistent with a pattern of beach reorientations along each shoreline segment. Beaches exposed to direct wave energy rotated clockwise (in map view), while beaches subject to refracted wave energy rotated counterclockwise.

Ecological zone width measurements and differences in backshore and foreshore beach slopes show that dry sand habitat was significantly reduced during the 1997-98 El Niño. Along dune-backed beaches, dry sand habitat narrowed but was sustained by migrating inland despite a drop in elevation. This drop in elevation expanded the lower intertidal zone widths (transforming dune and coastal strand habitats into beach habitat). During winter and early spring 1998 bluff backed shorelines completely lost dry sand habitat while lower beach habitats were largely converted to rocky substrate due to sand removal.

The abundance of macrophyte wrack, a primary food source for sandy beach food webs, was significantly correlated with the amount of dry sand habitat. Wrack abundance was depressed even prior to the onset of storm wave conditions and continued until 1999. The biomass of invertebrate populations was reduced and a decline in the mean size of individuals persisted for long-lived species, such as hippid crabs and clams. Overall abundance and species richness of shorebirds and the mean abundance of some common species (e.g. sanderlings, western sandpipers) were depressed during the El Niño event. In contrast, an uncommon shorebird (surfbird, *A. virgata*) that prefers rocky substrates was unusually abundant in the spring of 1998.

Beach segments recovered on different time scales, based on the littoral drift direction, with updrift beaches recovering first followed by downcoast beaches. Shoreline rotations caused during the El Niño recovered at different rates depending on the shoreline orientation. The downdrift beach suffered continued erosion more than 6 years after the El Niño storm season while at the same time, the updrift beach exhibited the widest beach widths shown in the air photo record. Recovery of wrack abundance and shorebirds to pre- El Niño levels took > 3 years. Reductions in the biomass and mean size of invertebrates were still detected 2 years after the El Niño. These physical and biological responses and timelines for recovery provide important information for coastal decision makers evaluating various erosion mitigation alternatives and habitat conservation planners faced with a paradigm shift from a single species focus to ecosystem-based management.

Keywords: Isla Vista, Santa Barbara, California, shoreline change, beach width, lidar, beach reorientation and rotation, large scale coastal behavior, storm disturbance, ecosystem-based management, intertidal, macrophyte wrack, invertebrate macrofauna, shorebird, sanderling, western snowy plover

INTRODUCTION

Extreme storm events can have disastrous impacts on infrastructure, property, recreational opportunities, and habitats along exposed coastlines. Sandy beaches are found on many exposed coastlines of the world (Bascom 1980). With rising sea level, a warming global climate, and exponential population growth, the reliance on beaches for recreation and habitat is increasing (Klein et al 2004, McLachlan and Brown 2006). A scientific understanding of the impacts of large storm events on both sandy beaches and their ecology is critically needed for the management of this dynamic zone to sustain coastal communities and habitats.

The occurrence of a major El Niño along the west coast of the United States can have lasting impacts to the coastline, humans, wildlife, and natural resources. Erosion during the 1997-98 El Niño reached devastating levels resulting in over $550 million in damages to property with 35 counties along the west coast declared Federal Disaster Areas (Griggs and Brown 1998, Komar 1986, Komar 1998, Storlazzi and Griggs 2000, Sallenger *et al.* 2002, Revell and Griggs 2006). El Niños alter normal west coast storm patterns affecting both wave characteristics and water levels. The two primary affects associated with El Niños are a southerly shift in the wave direction (waves tending to approach from the west and southwest) and elevated sea levels up to 30 cm above predicted tide levels. (Seymour 1984, Flick 1998, Kaminski *et al.* 1998, Seymour 1998, Storlazzi and Griggs 2000, Bromirski *et al.* 2003, Bromirski *et al.* 2005, Storlazzi and Wingfield 2005, Allan and Komar 2006).

The documented large-scale physical responses to extreme El Niño events on the west coast of Central California, Oregon, and Washington, USA involve a south to north rotation of beaches within west facing pocket beaches and littoral cells (Komar 1986, Komar 1998, Storlazzi and Griggs 2000, Sallenger *et al.* 2002; Revell *et al.* 2002, Ruggiero *et al.* 2005). This rotation has been attributed to the increase in wave heights as well as the shift in wave direction with waves coming from a more west and southwest angle than the more normal northwesterly direction (Komar 1986, Sallenger *et al.* 2002, Storlazzi and Griggs 2000, Revell *et al.*2002). During the 1997-98 winter, wave heights were higher than during the 1982-83 El Niño throughout the Northeast Pacific, but the storm track displacement was less extreme than the southern displacement of storms during the 1982-83 event (Bromirski *et al.* 2005).

Besides contributing to elevated water levels, the excursion of warm water propagating northward as a result of the relaxation of the equatorial trade winds also suppresses the normal upwelling intensity that is largely responsible for the delivery of nutrients into the coastal ocean (McGowan 1984; Otero and Siegel 2004).

Suppression of upwelling and nutrient delivery, reduces the production of phytoplankton, kelp, and other marine macrophytes (Otero and Siegel 2004; Reed *et al.* 2006) with effects propagating up coastal and pelagic food webs. This northward excursion of warm water can also alter patterns of larval recruitment, survival, and migration for marine populations (Hubbard and Dugan 1989, Raimondi *et al.*2002, Edwards and Estes 2006; Reed *et al.* 2006).

The physical effects of El Niño events on beaches have significant ecological implications for this coastal habitat yet little is known about the ecological responses to and recovery from El Niño events for southern California beaches. Direct ecological effects of El Niños on beaches could result from the high mortality of animals associated with loss of sandy habitat as has been documented for Peruvian beaches (Arntz *et al* 1987). Warm water, low nutrients, and storm wave disturbance to kelp forests and reefs can reduce the availability of macrophyte wrack to beach consumers. Larval supply and recruitment of invertebrates could be affected by mortality of adults, changes in currents and a lack of suitable settlement habitat. Reductions in prey availability for shorebirds could affect their survival and fitness, while loss of beach nesting habitat could restrict reproduction for species such as the Western Snowy Plover. Beaches may be particularly important as resources for shorebirds in southern California because of the extensive historical loss of coastal wetland habitats in this region (Hubbard and Dugan 2003).

El Niño events have played a major role in shaping the beaches and shoreline in Santa Barbara County as evidenced by the 1982-83 El Niño that significantly reduced beach widths by over half with beach widths never recovering to pre-1982-83 levels (Revell and Griggs 2006). El Niño storm patterns have been shown to reduce the wave sheltering effect in the Southern California Bight resulting in the largest increases to wave heights occurring in locations where the average extreme wave heights are typically lowest (Graham 2003). Several of these lowest energy locations are along the south facing beaches of the western Santa Barbara Channel (Figure 1).

This study investigates El Niño impacts for south-facing beaches, with the primarily unidirectional wave climate driving unidirectional alongshore sediment transport, and to integrate physical and ecological impacts on beaches. We combine topographic lidar data with physical measurements of sand heights, beach zone widths, and slope changes, and then investigate biological responses using ecological indicators of wrack, invertebrate macrofauna, and shorebirds. These data sets taken at comparable and overlapping scales enable an interdisciplinary look at the physical and biological impacts of the 1997-98 El Niño and the subsequent recovery, providing insights for coastal management, habitat conservation, and ecosystem-based management.

Setting

The Southern California Bight is located at the convergence of oceanic current regimes, marine biogeographic regions and terrestrial ecological transition zones

(Dailey *et al.*1993). The presence of Point Conception to the northwest, and the Channel Islands to the south create a narrow swell window that shelters much of the south facing coast of Santa Barbara County from extreme waves (Figure 1 inset). The Mediterranean climate of

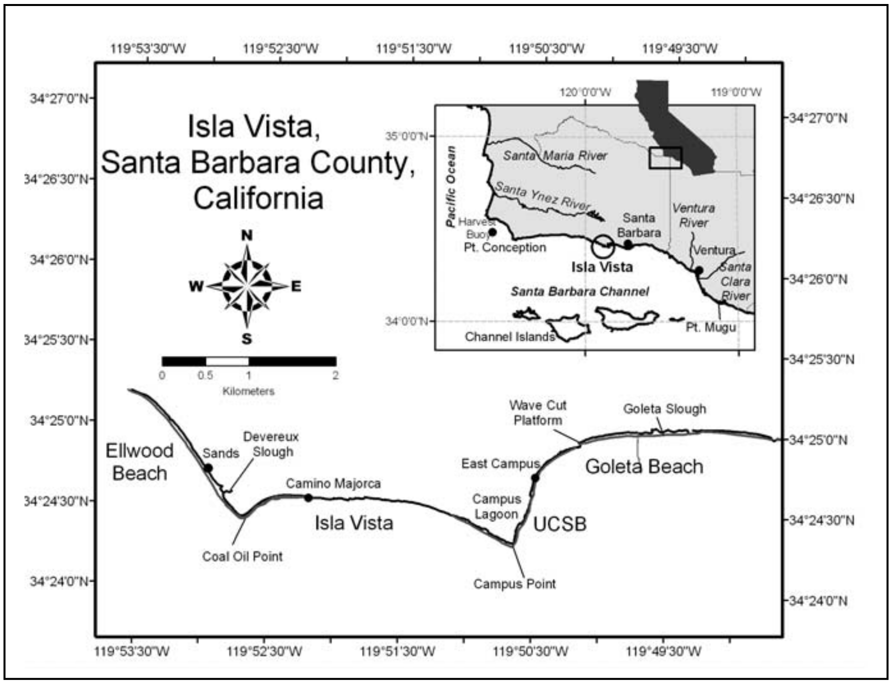

Figure 1: Isla Vista Coast, Santa Barbara, California, USA

southern California results in mild annual temperatures (~18ºC) and precipitation (~46 cm) punctuated by episodic and often extreme events. Winds and wave heights vary seasonally but focusing of waves into the Santa Barbara Channel drive an almost unidirectional alongshore transport in which beaches narrow during the winter and spring (November to April), and widen during the summer and fall (May to October). Longshore transport rates for the site are approximated by the Santa Barbara Harbor dredge records 18 km downcoast (east). The 70-year dredge record shows a mean annual rate of ~230,000 m^3 of sand removed per year (Patsch and Griggs 2007), although variability in the dredge volumes stem from sediment supply, navigational depth requirements and funding. The southern coast of Santa Barbara County is composed mostly of bluff-backed beaches perched on bedrock platforms. Along this coast are also a few dune-backed beaches formed near ephemeral creeks and sloughs, typically controlled by the complex faulting of the Western Transverse Ranges.

The present study focuses on 10 kilometers of narrow, south-facing beaches of the Isla Vista coast adjacent to University of California, Santa Barbara (UCSB). The study area was divided into four beach segments based on distinct shoreline orientations (Figure 1). The Ellwood segment from Ellwood to Coal Oil Point (2.5 km) is dune-backed and faces southwest into the dominant wind and wave direction. The Isla Vista segment (3.3 km) stretches from Coal Oil Point to Campus Point, faces primarily south and is backed by bluffs composed of Sisquoc shale with a thin lens of marine terrace sand on top of a bedrock platform. The southeast facing UCSB segment (1.5km) stretches from Campus Point to a wave-cut platform to the east and is backed primarily by a Sisquoc/Monterey shale bluff with several portions backed by riprap. Goleta Beach (2.3 km) faces south and stretches from the wave cut platform in the west to a rocky outcrop on the eastern side of the Goleta Slough. This shoreline used to be a sandspit with dunes, separating Goleta Slough from the Pacific Ocean, but was stabilized with fill in the mid 1940s and then riprap at various locations through what is now Goleta Beach County Park (Moffatt and Nichol 2002).

Erosion at this park resulted in placement of emergency riprap in 2000 and again in 2002 with several opportunistic beach nourishment projects. This continuing erosion at Goleta Beach resulted in a series of workshops between stakeholders and decision makers tasked with identifying preferred erosion mitigation alternatives. Portions of this research were presented and grew out of management related questions that arose in conjunction with these stakeholder worskhops.

The beaches of the Isla Vista coast provide habitat to a remarkably high density and diversity of beach invertebrates and shorebirds that are among the highest reported anywhere in the world (Hubbard and Dugan 2003, Dugan *et al*. 2003). Beaches in the study area receive large subsidies of drift marine macrophytes from extensive nearshore kelp forests, surfgrass beds, and reefs (>500kg m^{-1} yr^{--1})(Dugan *et al*. 2003, Lastra *et al.* submitted) that support high numbers of wrack consuming invertebrates. The high abundance, and biomass of macroinvertebrates on the study area beaches can include dense populations of long-lived suspension-feeding species, such as clams and sand crabs (Dugan *et al*. 2003). Beach invertebrates of all types are prey for shorebirds and fish.

The 1997-98 El Niño Signal

Waves and Water Levels

Analyses of hourly wave data from the Harvest Platform Buoy (Figure 1) (CDIP Buoys 071 and 063) show that the 1997-98 El Niño exhibited anomalous wave heights and more westerly wave directionality compared to the long-term combined directional data set (1993-2006) (Figure 2). Wave periods (not shown), did not differ significantly from other years. February 1998 was the most extreme monthly average on record,

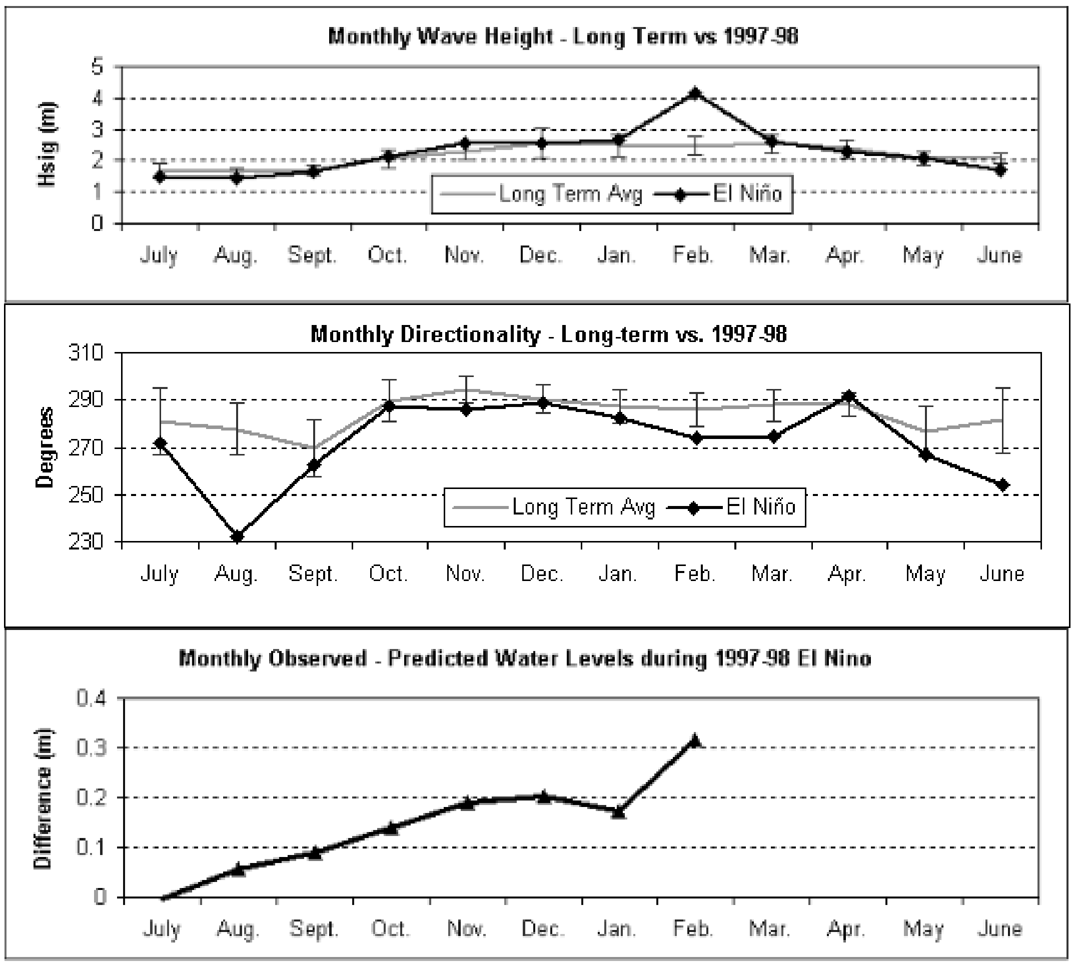

Figure 2. Mean monthly wave heights, (b) mean monthly wave direction from Harvest Platform, and (c) mean monthly water levels at Santa Barbara Harbor during the 1997-98 El Niño. Note that the 1997-98 data was removed to calculate the long-term averages.

with average monthly wave heights over 4m (4.1 m vs. 2.5 m – 14yr monthly mean) (Figure 2a). During February and March, extreme waves approached from a more westerly angle than normal (274º vs. 286º – 14yr monthly mean)(Figure 2b), well within the narrow swell window between Point Conception and the Channel Islands. These extreme wave heights with westerly swell angles increase wave energy along the normally sheltered study area and increased longshore sediment transport. Water levels taken hourly at the Santa Barbara Harbor tide gauge records show observed water level elevations higher than predicted tide levels, similar to results reported for San Francisco, Los Angeles, and La Jolla (Flick 1998). Between October 1997 and February 1998, monthly water levels averaged >15 cm above predicted (Figure 2c). Water levels reached maximum values of 30 cm above predicted before the gauge failed on February 3rd during the largest wave event (6.7 m) of the winter. Most of the highest waves, however, did not correspond with the highest tides of the year, thereby reducing the potential magnitude of erosion and property damage compared to the 1982-83 event (Flick 1998, Griggs and Brown 1998).

Precipitation

El Niños in southern California are largely associated with heavy precipitation years. Annual average rainfall in Santa Barbara based on records dating back to 1867 is 46 cm. The 1997-98 water year had the highest rainfall in the 138-year record and showed a 258% increase above the mean to 119 cm, including 53 cm of rain falling in February 1998. Sediment flux during an El Niño flood can average as much as 27 times higher than annual sediment flux during a dry period in these watersheds draining the western Transverse Ranges (Inman and Jenkins 1999). This high sediment yield may also have manifested as hyperpycnal discharges when the suspended sediment concentration raises water density above seawater resulting in a bottom boundary flow that may result in sand lost from the nearshore system. (Warrick and Milliman 2003). Thus while there was potential for significant sediment discharge and an increase in sand supply, there is also a chance that much of this material did not stay in the nearshore.

METHODOLOGY

This study coupled topographic lidar surveys with beach width measurements and biological surveys to help understand coastal responses to the 1997-98 El Niño. These data sets were collected separately, but at comparable temporal and spatial scales.

Lidar and Aerial Photography

On October 25th and 26th, 1997 and April 12th, 1998, NOAA, NASA, and the USGS collaborated to collect LIDAR data along 1200 km of the west coast providing a before and after glimpse of the 1997-98 El Niño (Sallenger *et al.* 1999). The lidar Airborne Topographic Mapper (ATM) data were collected using a first return sensor with accuracies reported as approximately 1 meter in the horizontal and 15 cm in the vertical (Sallenger *et al*. 1999, 2003). First return data were edited to remove noise from vegetation, rooftops, and potential seabirds in flight. This pre-post- storm sampling captures both the typical winter seasonal beach change signal and an El Niño response.

A Mean High Water (MHW) shoreline reference feature (1.4 m NAVD88) based on the Santa Barbara Harbor tidal datum records was digitized in ArcGIS. A backshore reference feature representing the toe of the dune or bluff was also digitized based on visual cues from slope, curvature, and hillshade layers derived in ArcGIS. The datum shoreline and the backshore reference line were analyzed at transects spaced 50 m apart alongshore using the USGS Digital Shoreline Analysis System 3.1 (DSAS; Thieler *et al.* 2005). Beach widths (m) and volumes (m^3/m) between MHW and the back beach reference feature and shoreline change at the MHW, 2m and 3m elevations, and back beach were computed at each transect. Backshore beach slopes were calculated from the elevation of the backshore reference line and the distance to the MHW shoreline. Volume changes were calculated between each 50m transect then summed alongshore to quantify the total volume changes (m^3) per beach segment. Average volume changes between transects was also calculated for each shoreline segment.

Shoreline reference features representing the back beach and the wet/dry line digitized from rectified aerial photography in 2001 and 2003 were used to examine the recovery of the beaches following the 1997-98 El Niño (Revell and Griggs 2006). The wet/dry line was tidally corrected to MHW by adjusting the beach widths based on the tide level at the time of the photo and an average summer beach slope extracted from historic beach profiles (Revell and Griggs 2006). This adjustment is based on the tidal component of a total water level discussed by Ruggiero *et al.* (2003) and Moore *et al.* (2005). Transects were cast at the same 50 m spacing using DSAS 3.1 (Thieler *et al.* 2005). To examine recovery, five transects taken at the ends and midpoint of each shoreline segment were averaged and plotted to examine the shape of the beach (concave versus convex) as well as the persistence of rotations.

Biological Methods and Physical Measurements

Three cross-shore transects extending from the landward boundary of the beach (the lowest edge of terrestrial/dune vegetation or the base of the seacliff) to below the lowest swash level (~MLLW) were surveyed monthly on each shoreline segment. Distances between transects were randomly selected, but a minimum distance of at least 10 m between transects was used to avoid disturbance of mobile macrofauna.

To estimate the standing crop of macrophyte wrack, the cover and composition of wrack were measured monthly using a line intercept method along the same three transects for each segment. All wrack, debris, driftwood, carrion, or tar of 1 cm or more in width that intersected the one meter transect line was measured, categorized, recorded. The total width of wrack encountered was totaled for each transect. Mean values of wrack cover were calculated for the three transects at each site and date and expressed as m^2/m of beach.

To estimate the species richness, abundance, and biomass of the macrofauna community, core samples were collected on spring low tides in September/October of 1996 and again in September/October 1999 using methods described in Dugan *et al.* 2003. Each transect was sampled with 15 uniformly spaced cores of 10 cm diameter and 20 cm depth. Core sediments were washed through a 1 mm sieve, retaining the macrofauna. This sampling design yielded a total sampling area of 3.5 m^2 and a total of 45 samples (15 per transect) along each shoreline segment. Means of abundance and wet biomass of macrofauna were calculated and expressed as numbers of individuals or grams/m of beach (Brown and McLachlan 1990).

To characterize shorebird use, birds were surveyed monthly along a standard 1 km alongshore transect on Isla Vista during morning hours. Typically birds were counted while walking through dry sand habitat on the outward leg and along the low intertidal during the return leg. Shorebirds were identified to species level and birds in flight were not counted. Additional survey details are available in Hubbard and Dugan 2003.

Several physical characteristics including ecological zone widths and beach slopes- were also measured monthly as part of the biological surveys along the three cross-shore transects. The widths of ecological zones were measured from the seaward edge of terrestrial/dune vegetation or toe of the bluff (the same back beach feature identified in the lidar and air photo data) to the lowest swash level (Figure 3). The width of the active intertidal zone, and the distances from the back beach to the driftline (dry sand) and to the water table outcrop (WTO), were measured and reported as monthly means from 1995-2001. Weekly dry sand beach widths were collected along Ellwood and the western portion of Isla Vista Beach during 1999 (Lafferty 2001, USGS unpublished field data). For beach width comparison with the lidar and air photos, the dry sand ecological zone width extending from back beach to the driftline was used. Comparisons of 1997 lidar beach widths with the physical measurements of the dry sand zone for the same time period, fell within +/- 1 meter horizontal accuracies reported for lidar data. Foreshore beach slopes were measured monthly at the water table outcrop (WTO) using a one-meter electronic level and recorded in degrees.

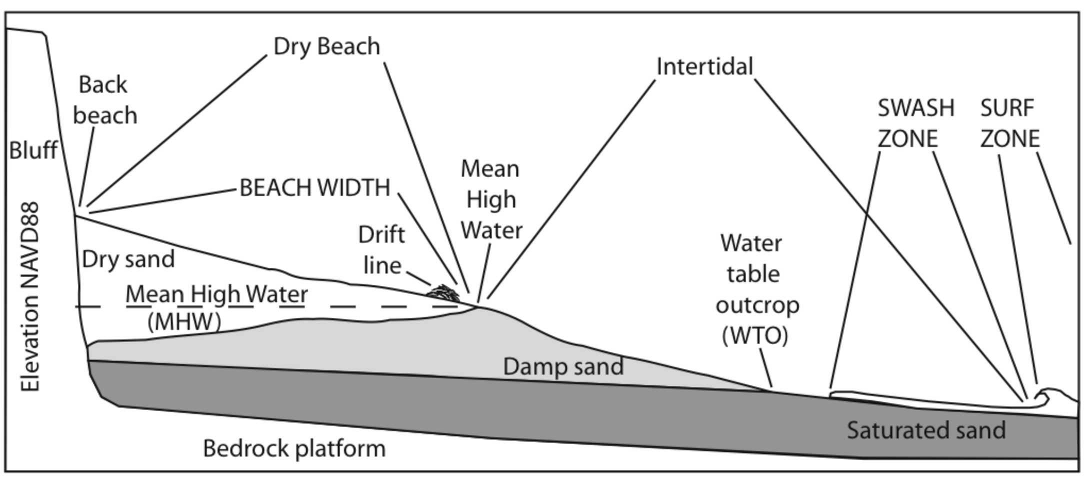

Figure 3. Ecological zone widths at low tide and beach terminology

Sand Heights

Sand height measurements were taken 10 to 12 times per month at 3 sites from August 1996 and October 2001 at Sands (Ellwood), Camino Majorca (Isla Vista) and

East Campus (UCSB)(Figure 1). Sand heights were measured from the top of fixed features near the shoreline to the sand level on the beach. As a result these data record relative elevation changes not related to a vertical datum, but show fluctuations at monthly, seasonal and inter-annual time scales.

Beach Reorientation

To examine the patterns of volume changes on the individual shoreline segments, the average volume changes for each segment was removed from each individual transect on that segment (Revell et al. 2002). The residual volumes at each transect were then summed cumulatively alongshore from west to east (downdrift). This method forces the alongshore volume changes to zero at the beginning and end of each shoreline segment revealing the response of the sand remaining on each beach segment. Note that for each shoreline segment (e.g. Ellwood, Isla Vista) a different average volume was removed based only on changes occurring along that shoreline segment.

RESULTS

The 1997-98 El Niño resulted in major physical impacts to the beaches along the study area. These impacts can be seen in the shoreline change and changes to beach widths and sand volumes. Several erosion hotspots developed at Ellwood, at the west end of Isla Vista, and at Goleta beaches. These physical changes impacted the amount and quality of habitat resulting in significant changes to ecological indicators of wrack, macrofauna invertebrates, and shorebirds.

Physical Changes

Distinct differences in shoreline and beach width changes could be identified based on backshore type. Along the dune-backed beaches like Ellwood and Goleta, the shoreline change across the profile was relatively constant across the contours. Higher levels of back beach retreat provided evidence that in dune-backed systems the beach was able to migrate inland maintaining a relatively wider beach width (Table 1,2).

Shoreline Retreat (m)	Ellwood (m)	Isla Vista (m)	UCSB (m)	Goleta (m)	Averages (m)
Backshore Type	*Dune*	*Bluff*	*Bluff*	*Dune*	
MHW (1.4m)	*23.4*	*13.0*	*16.7*	*25.8*	*18.9*
2 m	*20.3*	*9.3*	*12.1*	*27.7*	*16.2*
3 m	*23.5*	*5.3*	*3.1*	*22.0*	*13.3*
Back beach	*6.9*	*2.7*	*1.4*	*3.7*	*3.7*

Table 1: Shoreline changes of different features (elevations are based on NAVD88)

Beach Width Above MHW	Ellwood (m)	Isla Vista (m)	UCSB (m)	Goleta (m)	Averages (m)
1997	*41.2*	*19.0*	*22.4*	*41.6*	*30.5*
1998	*16.1*	*7.5*	*5.3*	*13.3*	*11.7*
Change	*25.1*	*11.5*	*17.1*	*28.3*	*20.5*
% Change	*61*	*60*	*76*	*68*	*67*

Table 2: Average beach widths in 1997 - 1998 and changes over the El Niño season.

Along the bluff-backed segments of Isla Vista and UCSB, the lower beach contours retreated most while the back beach erosion was limited by the hardness of the bluff. UCSB lost the greatest amount of relative beach width (76%)(Table 2). The result of these physical changes was the loss of much of the sandy habitat along bluff backed shorelines with a conversion to primarily rocky substrate, and a reduction of dry sand ecological zones along dune-backed shorelines. Our time series of monthly measurements of ecological zone widths show that while the overall beach widths along dune-backed Ellwood maintained an overall width of ~40m (back beach to WTO), the width of the dry sand zone (back beach to driftline) at the top of the profile narrowed, while the lower intertidal zones expanded during the El Niño event. The widths of this dry sand zone showed a strong seasonal signal and a response to the 1997-98 El Niño at Ellwood and UCSB. Seasonally, on the bluff-backed beach at UCSB, the dry sand zone is reduced to near zero for three months each year, but during the 1997-98 El Niño, this zone was not detectable (width reduced to zero) for at least 8 months and remained relatively narrow through 1999. At Ellwood, the width of this dry sand zone was generally wider and more variable but it became very narrow (≤5m wide) for 6 months during the 1997-98 El Niño. It should be noted that the reduction in the width of this dry sand zone occurred at Ellwood, even though the back beach eroded into the dunes. These effects can also be seen in the beach slope and contour retreat data (Tables 1, 3).

Beach Slope Changes

Backshore beach slopes measured in the lidar data steepened in response to the 1997-98 storm season while foreshore beach slopes measured by electronic level at the WTO, show a flattening of the lower beach slope (Table 3). These slope changes

Slopes (tanβ)	Ellwood	Isla Vista	UCSB	Goleta
Lidar 1997	0.055	0.093	0.077	0.045
Lidar 1998	0.064	0.145	0.134	0.075
WTO 1997	0.048	0.073	0.066	0.068
WTO 1998	0.038	0.052	0.048	0.052

Table 3: Beach slopes (tanβ) –backshore extracted from Lidar and foreshore slopes (monthly means for October and April) measured at the water table outcrop (WTO).

are consistent with the widening of the lower intertidal zone width and reduction of the dry sand portion of the profile along the dune-backed Ellwood and Goleta Beach segments. Steep beach slopes found along bluff-backed Isla Vista and UCSB segments resulted from near complete loss of the beach width.

Beach Volume Changes

Lidar data with its detailed topographic information enables volume change to be measured for the various shoreline segments (Table 4) as well as show the volume changes between the surveys (Figure 4). In 1997, there were approximately 490,000 m^3 of sand above MHW on the beaches in the study area. During the El Niño, ~390,000 m^3 (80%) of sand was removed from the beaches so that by April 1998, there were only ~100,000 m^3 of sand remaining. This volume change represents the combination of both seasonal effects and El Niño impacts. All beaches lost at least

Volume	Ellwood	Isla Vista	UCSB	Goleta	All Segments
1997 volume (m^3/m)	84	30	40	94	54
1998 volume (m^3/m)	25	6	3	15	11
Average volume change (m^3/m)**	60	24	38	79	50
Total Beach Volume Change (m^3)	125,202	79,454	50,233	134,258	389,148
% Change	71	80	95	84	93

Table 4: Beach volume changes during the 1997-98 El Niño. **used in figure 5

70% of the sand volumes, with UCSB losing 95% of its pre-El Nino volume. The dune-backed beaches of Ellwood and Goleta suffered the greatest absolute losses. The total volume changes at each transect between the lidar surveys were plotted

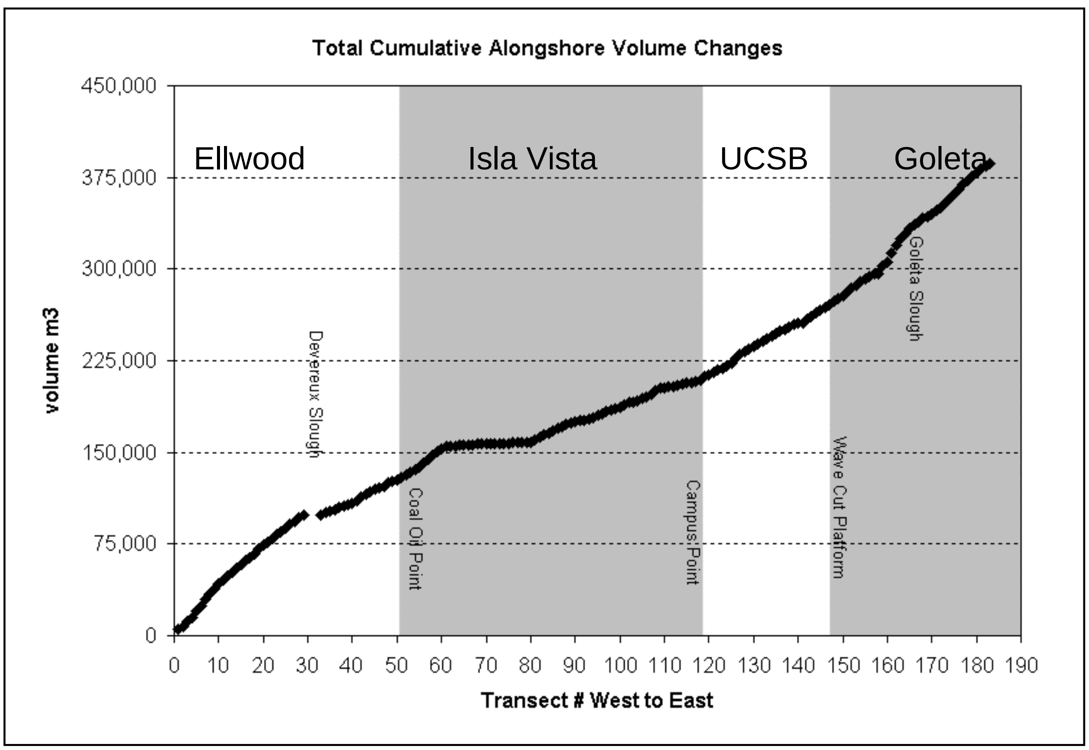

Figure 4: Total alongshore volume changes between October 1997 and April 1998.

cumulatively alongshore showing a pattern of increasing volume change downdrift (Figure 4). The slope of this line shows the longshore transport gradients with steeper slopes indicating more rapid volume changes occur at west Ellwood and east Goleta.

Erosion Hotspots and Beach Reorientation

To examine the response of the beach to these large volume changes across the individual shoreline segments, we isolate the sand volume remaining on the beaches using the average volume changes per segment and cumulative residuals (Figure 5).

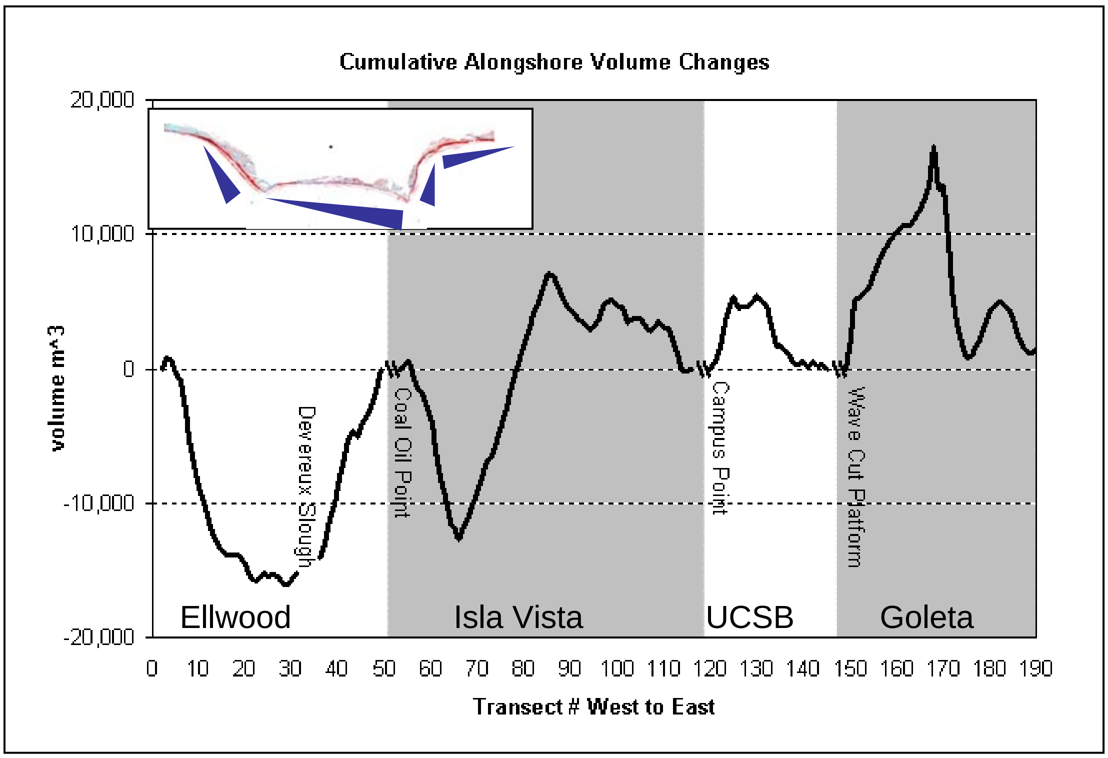

Figure 5. Cumulative alongshore volume changes during the 1997-98 El Nino. Average beach segment volume changes for each shoreline segment (see table 4**) were removed from individual transects and the residuals were summed alongshore from west to east (downdrift). Note each beach segment (shaded) had a different average volume change removed. Inset figure shows the direction of beach rotations for each segment.

This method forces the cumulative volume changes for each shoreline segment through zero at the end of the segment, revealing a pattern of beach reorientation consistent with the observed locations of the erosion hotspots found at the west ends of Ellwood and Isla Vista, and the east ends of UCSB and Goleta. These data show that Ellwood and Isla Vista rotated clockwise while UCSB and Goleta rotated counterclockwise (Figure 5 inset).

Physical Beach Recovery

Scales of beach recovery were examined using sand heights and rectified air photo derived beach widths (Figure 6, 7). Mean annual sand height elevations show the impact of the 1997-98 El Niño (Figure 6a). The low elevations observed in 1998 were followed by a recovery period with sand elevations in 1999 at all sites surpassing those measured in 1997. A time series of monthly mean sand elevations shows additional details of this sand recovery following unidirectional longshore sediment transport with the upcoast Ellwood segment recovering sand first by fall 1998 from the lowest elevations measured in February 1998 (Figure 6b). Downdrift beaches recovered more slowly with pre-El Niño sand elevations reached by summer 1999 at Isla Vista and by fall 1999 at UCSB. Recovery of sand elevations continued at Ellwood through 2001 coinciding with the widest beach widths observed in the historical air photo data.

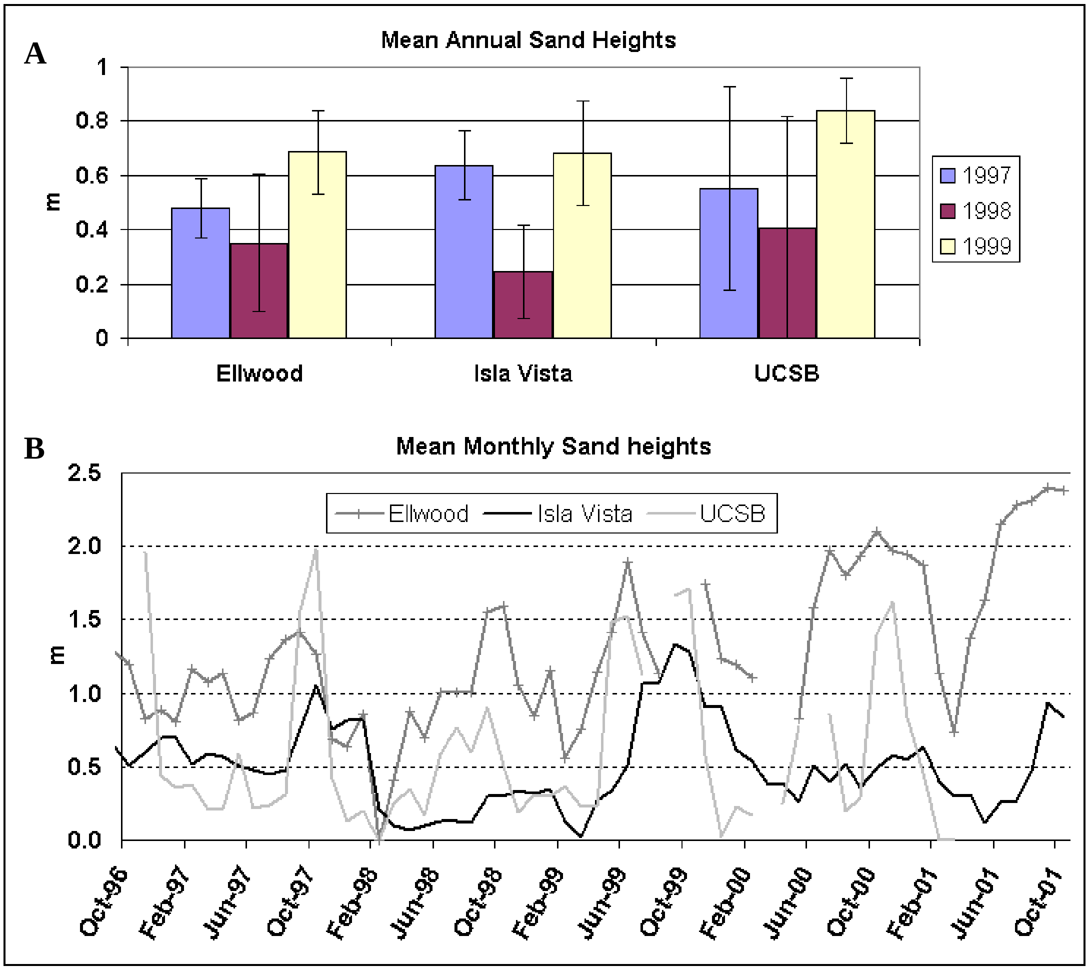

Figure 6: (a) Mean annual sand heights 1997-1999 (± 1 std. deviation) and (b) Mean monthly sand heights 1996-2001.

Beach reorientation was also detected by analyzing beach widths along transects at the endpoints and center point of each shoreline segment (west, center and east). Higher beach widths on the west side transects indicate a counterclockwise orientation, and the higher beach widths on the east side transects indicate a clockwise orientation (Figure 7). Examination of these endpoint transects show the persistence of the beach reorientations and recovery of beach widths. Recovery of the dry beach widths at Ellwood in 1999 show that while beach widths recovered, the reorientation persisted until sometime between 2000-2001 (Figure 7). Evidence of the beach rotation at Ellwood were gone by 2001 when beach widths showed a full recovery to widths previously unseen in the historic air photo record (Revell and.

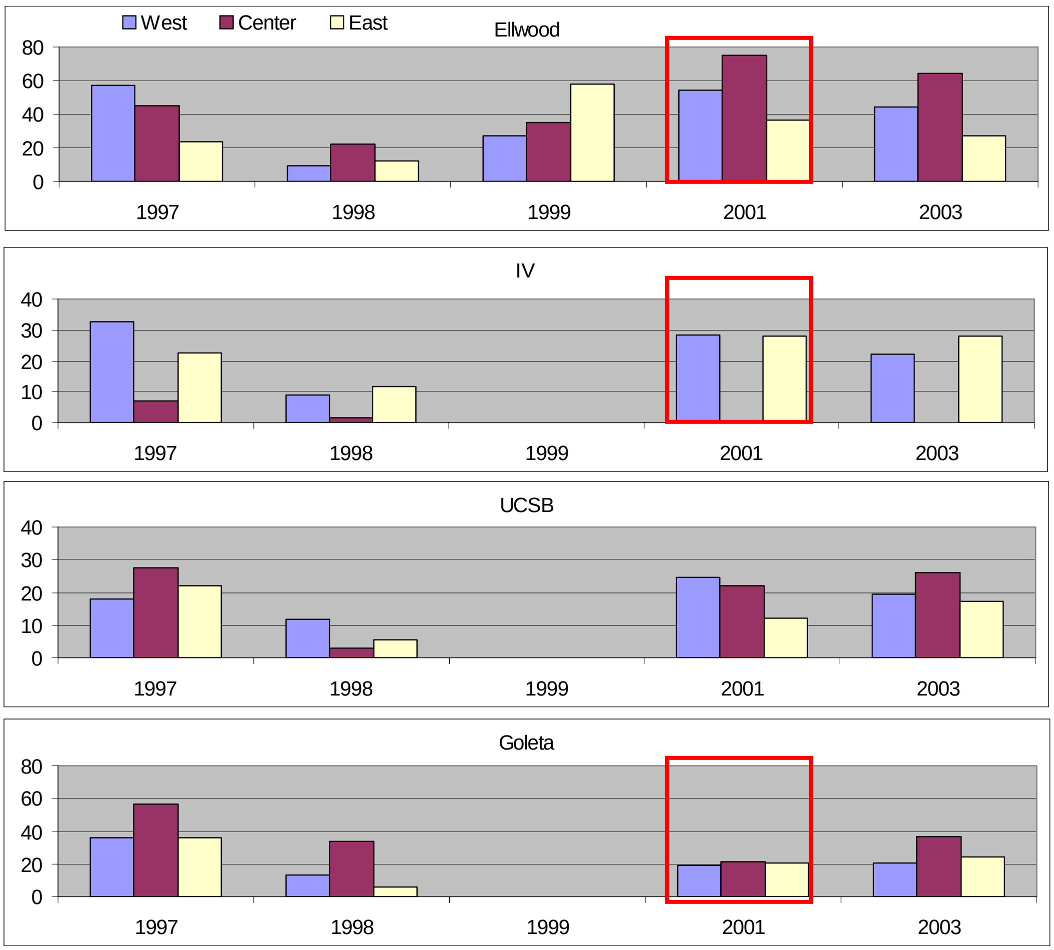

Figure 7: West, Center and East end beach width (m) averages for years following the El Niño showing the beach rotations and recovery time for each beach to return to 1997 configuration. 1997 and 1998 data is from lidar, 1999 data is from USGS unpublished field measurements, and 2001 and 2003 are from rectified air photos. Note that the beach width scales are the different for the respective shoreline segments. Boxes show recovery of rotations.

Griggs 2006). The rotation at Isla Vista also recovered by 2001, but the beach at the center of the segment had yet to recover by 2003. The rotations visible at UCSB remained throughout 2003 although beach widths neared full recovery by 2001. At Goleta Beach the rotation recovered by 2001, but the beach widths remained relatively narrow. A short series of sand height data collected from Goleta (not shown) shows steady declines in sand elevations from 1999 to 2001.

Biological Impacts

The physical changes impacted the amount and types of habitat available for species as previously discussed resulting in significant changes to ecological indicators of wrack, macrofaunal invertebrates, and shorebirds.

Wrack

The abundance of marine macrophyte wrack exhibited seasonal variations with maxima in the fall and minima in late winter and spring at Ellwood and UCSB during all 6 years of the time series (Figure 8). During the 1997-98 El Niño the mean cover of wrack dropped to the lowest annual maxima observed in the study period. Wrack cover declined to near zero and remained low at Ellwood and UCSB for a prolonged period between January and July 1998. Mean annual wrack cover (October to September) during the 1997-98 El Niño was 40% and 31% of the values in the previous year (1996-97) at Ellwood and UCSB, respectively. Wrack cover at these two sites did not reach or exceed the 1996-97 levels for at least three years after the

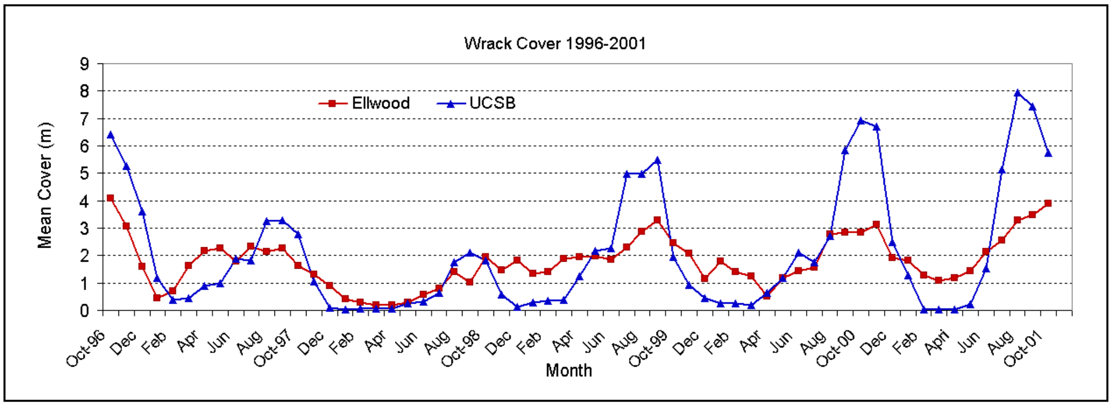

Figure 8. Mean monthly cover of marine macrophyte wrack for the study beaches at Ellwood and UCSB for 1996-2001 (3 month running means smoothed)

El Niño event ended. Mean wrack cover was significantly correlated ($p < 0.05$) with the width of the dry sand zone for both sites for 1996-2001.

Invertebrates

Comparisons of samples of the invertebrate community collected in late summer one year before (1996) and 2 years after (1999) the 1997-98 El Niño on the same transects at Ellwood and UCSB allow us to evaluate responses of beach invertebrates to the 1997-98 El Niño that persisted over time but not the immediate responses to that event. The extreme loss of sandy habitats immediately following the event precluded comparable quantitative sampling in the late summer of 1998 at these sites. Responses varied between beach sites and among different invertebrate community and population characteristics. Total invertebrate community biomass was lower in 1999 than in 1996 at both sites (36%, UCSB; 52%, Ellwood) as was mean individual size (mass) (70%, UCSB; 40%, Ellwood) (Table 5). No consistent variation in the species richness or total abundance of beach macroinvertebrates was detected 2 years after the El Niño.

Population abundance and biomass were lower for long-lived invertebrate species, the hippid crab, *Emerita analoga,* the venerid clam, *Tivela stultorum*, and the bean clam *Donax gouldii*, 2 years after the El Niño (1999) than before (1996) (Table 5).

Invertebrate Characteristic	**Ellwood**		**UCSB**	
	1996	**1999**	**1996**	**1999**
Community Measures				
Species richness	31	30	37	38
Abundance # m-1	30272	22664	42246	91673*
Biomass g m-1	5940	2831^	4317	2743
Mean Individual Size (g)	0.196	0.125	0.102	0.03^
Population measures				
Emerita analoga				
Abundance # m-1	7367	6366	2406	1817
Biomass g m-1	3467	2195	1317	388*
Mean Individual Size (g)	0.471	0.345**	0.547	0.214*
Tivela stultorum				
Abundance # m-1	446	229		
Biomass g m-1	1423	199		
Mean Individual Size (g)	3.191	0.869		
Donax gouldii				
Abundance # m-1	357	102*		
Biomass g m-1	128	69		
Mean Individual Size (g)	0.359	0.677		
Megalorchestia spp.				
Abundance # m-1	7190	6621	10205	61098
Biomass g m-1	63	65	378	1655
Mean Individual Size (g)	0.009	0.01	0.037	0.027

Table 5. Beach invertebrate community and population characteristics in 1996 and 1999 (^ p <0.08, * p<0.05, **p<0.001, ***p<0.001 for one way analysis of variance (ANOVA) on log transformed data.

For *E. analoga*, population biomass was 37% and 70% less at Ellwood and UCSB respectively. The mean individual size of *E. analoga* was 36% lower at Ellwood and 70% smaller at UCSB in 1999 compared to 1996. For *T. stultorum,* which occurred only in samples from Ellwood, population biomass was 86% lower and mean individual size was 73% smaller in 1999 than in 1996 (Table 5). Abundance and population biomass of the bean clam, *Donax gouldii* was also lower in 1999, but not mean individual size. No consistent variation in population abundance, biomass and mean individual size of the short-lived talitrid amphipod, *Megalorchestia* spp. was detected 2 years after the El Niño.

Shorebirds

Shorebird use of the beach at Isla Vista is highly seasonal with peaks in abundance and species diversity during the fall and winter months. The lowest overall abundance and species richness of shorebirds during the 6-year study period (1995-2001) was observed during and immediately following the 1997-98 El Niño (Figure 9 data from Hubbard and Dugan 2003). Mean annual abundance of shorebirds preceding the El Niño (1995-1997) was 131 birds km^{-1}. In 1998, mean annual shorebird abundance dropped to 76 birds km^{-1} (60% of pre-El Niño average). Shorebird numbers remained low (annual mean of 82 birds km^{-1}) through 1999 and did not recover to pre-El Niño levels by early 2001, when mean annual abundance was 98 birds km^{-1} (data from Hubbard and Dugan 2003). The species richness of shorebirds was also lower during the El Niño in 1998 than in other years of the study, at 4.9 species per km (5.3, 5.7 and 5.7 species per km in 1995, 1996, and 1997 respectively) (data from Hubbard and Dugan 2003). However, species richness of shorebirds recovered more rapidly than abundance. By 1999, shorebird richness was 6.0 species km^{-1}, exceeding the pre-El Niño levels for this beach.

Sanderlings (*Calidris alba*), although highly seasonal, were the most abundant shorebird species during the study, with mean annual abundance averaging 76 birds km-[1] before the El Niño (1995-1997) (Figure 9). During the El Niño the abundance

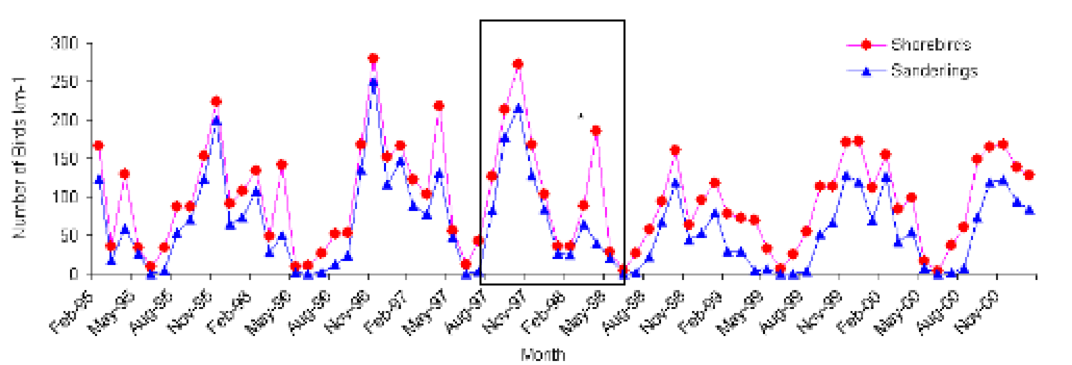

Figure 8. Mean monthly abundance of Sanderlings and shorebirds on the Isla Vista beach transect (data from Hubbard and Dugan 2003). Box denotes El Niño period.

of Sanderlings dropped to 42 birds km^{-1}. The mean annual abundance of this species averaged 40 birds km^{-1} in 1999 and the abundance of Sanderlings on the transect had not recovered to pre-El Niño levels by early 2001. Reduced abundance of this species was the most important factor in the decline of shorebird abundance observed in 1998 and subsequent years.

During the 1997-98 El Niño, the abundance of several commonly observed species of shorebirds (Marbled Godwit, Black-bellied Plover, Willet, Whimbrel) also dropped to the lowest levels observed in the 6-year study period on Isla Vista beach. The abundance of these species returned to average levels more rapidly than Sanderlings. In contrast, the average abundance of the Surfbird (*Aphriza virgata*), a species usually associated with rocky shores, was more than 60 times higher in 1998 (9.3 per km) than the pre-El Niño average (0.14 per km). This species appeared in high numbers in April 1998 when large areas of rocky substrate exposed during the El Niño coincided with spring migration.

DISCUSSION

Physical Changes and Recovery

Significant variation in beach volumes, beach widths, and shoreline position observed among beach segments in response to an El Niño is largely related to backshore type. Along bluff-backed segments, beach widths narrowed, beach slopes steepened , and higher percentage changes in beach volume were documented. Along dune-backed segments, the migration of beach widths landward and down on the beach profile narrowed the dry beach zone while expanding the lower intertidal zones. This extreme erosion event served to eliminate much of the dry sand habitat and impact the ecosystem that depends on sandy beaches.

In the absence of historical beach profiles, sand height data quantifying the seasonal changes improves our ability to understand the impacts and subsequent recovery of beaches associated with the 1997-98 El Niño. However, despite seasonal signals evident in the sand height data, the limited spatial extent of the data precluded accurate assessment of seasonal volume changes across the entire study area.

Erosion hot spots identified along the Ellwood, Isla Vista, and Goleta beach segments are consistent with a pattern of beach reorientation that occurred during the 1997-98 El Niño. While most likely related to individual storm event characteristics, the causative mechanisms and timing for this shoreline rotation is not clear given the limited temporal sampling of the LIDAR data, and the limited spatial scale of the physical measurements. Beach rotations have been observed elsewhere as a response to a change in wave direction (Sallenger *et al.* 2002, Ranashange *et al.* 2004, Slott *et al.* 2006) but in previous reported cases, there tends to be a reversal in longshore transport, which is unlikely in this area given the unidirectional wave climate and longshore sediment transport. By rotating into the direction of prevailing waves, the longshore transport of sand would be reduced as the angle between the incident waves and the shoreline becomes more parallel. By remaining in this rotated state, longshore transport gradients at Ellwood would have been reduced potentially serving as a sand sink through the end of at least 1999 resulting in the persistence of downcoast erosion impacts along the UCSB and Goleta beach segments, which had not recovered in width by 2003 (Revell and Griggs 2006).

The recovery of the beach segments on different timelines may be a result of back beach type, rotation persistence, shoreline orientation, and upcoast sand supply. Despite losing 71% of its sand volume during the 1997-98 El Niño, and reaching the lowest sand levels detected in the 7 year sand height data set, the dune-backed Ellwood sand heights in February, reached heights greater than before the storm event. This increased level of sediment must have come from updrift and this observation provides some evidence that the increase in river sediment discharge from the heavy rains may have increased the sand supply to the system (Inman and Jenkins 1999).

The recovery of beach widths following the 1997-98 El Niño was more rapid than observed for the 1982-83 El Niño (Revell and Griggs 2006). This may indicate that for these south-facing beaches, the more extreme southern shift in the storm track associated with the 1982-83 event was more important than the higher wave heights reported during the 1997-98 El Niño (Bromirski *et al*. 2005). However it remains possible that it could have been the repeated simultaneous occurrence of high tides and storm waves in 1982-83 compared with less frequent occurrence in 1997-98.

Ecological Responses

Wrack

El Niño effects on kelp forests are associated with a combination of increased water temperatures, reduced nutrient availability, and intense disturbance from storms

(Dayton and Tegner 1984). The decline in abundance of macrophyte wrack at the study beaches was likely related to these strong effects of the El Niño on kelp forest ecosystems (Edwards and Estes 2006). During the 1997-98 El Niño only a small fraction (15%) of kelp forest patches in southern California were occupied by kelp canopy (Reed *et al.* 2006). Despite strong disturbances to kelp beds and other marine macrophytes that could dislodge kelp and temporarily increase wrack inputs, wrack abundance did not reach typical maximum levels during the 1997-98 El Niño.

A significant correlation found between wrack cover and dry beach zone widths suggest that wrack abundance and deposition is affected by the condition of the dry sand beach. When the uppermost dry sand zone of the beach is narrow or absent on a bluff-backed beach, or in front of a steeply eroded foredune, wrack deposition and retention is greatly reduced. Reduced accumulation and retention of wrack has been also reported for beaches with seawalls that have no dry sand zone (Dugan and Hubbard 2006).

The recovery of kelp forest ecosystems from El Niño events varies regionally (Edwards and Estes 2006). The persistence of low abundance of marine macrophyte wrack through June 1999 suggests that kelp forests and macrophyte beds did not recover rapidly in the study area.

Invertebrates

Variation in the responses of beach invertebrate species to El Niño events can be due to differences in life history and metapopulation dynamics. Mortality of intertidal invertebrates can be very high during storm events that erode beaches (Arntz *et al.* 1987). Subsequent recruitment of species with planktonic larval sources to beaches can also be affected by the loss of sandy intertidal habitat to storm wave erosion and elevated sea levels demonstrated here.

The significant decline in the mean individual size of sand crabs, *Emerita analoga*, one of the dominant intertidal animals of the sandy beaches of the study area (Dugan *et al.* 2003) was evident well over a year after the El Niño event suggesting that a combination of low survival of adults followed by depressed recruitment in the spring of 1998 occurred. The pismo clam, *Tivela stultorum*, also showed a strong decrease in size, biomass and abundance that persisted well over a year after the El Nino. This long-lived species (>20 years; Fitch 1950) only recruits sporadically to California beaches (Coe 1953; McLachlan et al 1996). The loss of larger and older cohorts of intertidal invertebrates (e.g. sand crabs, *Emerita analoga*, and Pismo clams, *Tivela stultorum)* may take 1 to 10 years for recovery. High mortality associated with storm waves and habitat loss and reduced availability of macrophyte wrack likely affected populations of wrack consumers on the study beaches as well, but recovery was evident by 1999 for wrack and for direct-developing animals with short generation times, such as talitrid amphipods.

Shorebirds

The response of shorebirds to the 1997-98 El Niño was evident in overall abundance and species composition on the study beach with abundance for all shorebirds declining by 42% and that of the dominant species, sanderling, declining by 30% during 1998. The most intense effects of the 1997-98 El Niño on beaches in the study area coincided with the months when shorebird use of these beaches is normally highest (Hubbard and Dugan 2003). Shorebirds appeared to respond to changes in beach habitat characteristics and prey availability during the El Nino. Prey availability for shorebirds on beaches was greatly reduced, particularly for lower zone invertebrates, such as sand crabs. The loss of wrack subsidies to intertidal consumers, such as amphipods and insects, also has major ecological implications for shorebirds. Wrack-associated invertebrates are often an important prey resource for shorebirds that is available on a wider range of tide levels than most of the suspension-feeding invertebrates. The loss of wrack and associated invertebrates results not only reduced prey availability but also foraging time for shorebirds.

Declines in the overall abundance of shorebirds on beaches in the study area persisted for several years following the El Niño. Most of the decline in abundance was driven by persistent low numbers of the most abundant shorebird, the sanderling (*Calidris alba*), which recovered more slowly than several other common species of shorebirds. Species richness of shorebirds returned to pre-El Nino levels within a year of the event while abundance remained depressed suggesting that abundance may be a more sensitive indicator of habitat loss, prey availability, and recovery.

Beach and Ecosystem Recovery

Several factors need to coincide for the recovery of beach communities from El Niño impacts. Sufficient sandy beach habitat across all ecological zones is needed for recruitment and recolonization of invertebrates to occur. Grain size and resulting beach slopes must be suitable for a variety of invertebrate species. Subsidies of phytoplankton and marine macrophytes must be available to support beach invertebrates. Then, a supply of recruits, including larvae from the plankton and juveniles produced by surviving adults of direct-developing species, is needed to rebuild populations on the beach. In addition, a simple recovery model may not be appropriate for beach invertebrate communities. Community composition and succession could potentially be affected by the mortality of dominant species and shifts in species ranges during El Nino events (e.g. Arntz *et al.* 1987). Once invertebrate prey resources become available, shorebird use of beaches can increase, however populations of some important shorebirds, such as sanderlings, may require longer recovery periods.

CONCLUSIONS

This interdisciplinary study utilized several unique data sets to quantify the impact of the 1997-98 El Niño along some of the south facing beaches of the Santa Barbara

Channel, to document the response of the coastal ecosystem, and to identify various time scales of recovery.

Peak El Niño impacts (sea level, wave climate and erosion) corresponded to the largest and most westerly storms occurring in February 1998. Overall the impact to the beaches was substantial, beach widths narrowed by greater than 60% and there was ~390,000 m^3 of sand removed from the beaches. Significant changes to beach volumes, beach widths, and shoreline positions were related to the type of back beach. Bluff-backed segments experienced greater percentages of beach volume changes along with a conversion of dry sand habitat to rocky substrate. Along dune-backed segments, the migration of the beach landward and down on the beach profile maintained some of the dry beach zone while expanding the lower intertidal ecological zones. The loss of dry beach habitat on all beaches was significantly correlated with the decline in macrophyte wrack available to consumers. This correlation proves the important connection between dry sand beach habitat and food supply. This connection provides an ecological indicator and potential monitoring tool for habitat conservation planning.

Several erosion hotspots were identified that match a documented pattern of beach reorientation. The rotation pattern shows that the beaches facing into the dominant waves rotated clockwise in the downdrift direction, while the beaches impacted by more refracted wave energy rotated in counterclockwise direction. These rotations persisted for more than a year and provide an indicator for beach recovery following the El Niño that could be incorporated into beach monitoring programs and evaluation of emergency shore protection permits.

This erosion of habitat and loss of food subsidies has implications for the entire sandy beach ecosystem. The El Niño event resulted in a reduction of biomass of sandy beach macrofauna invertebrates and a decline in the mean size of the individuals. The mean abundance and species richness of shorebirds were depressed and an uncommon shorebird (surfbird, *Aphriza virgata*) found on rocky substrates was unusually abundant.

Coastal response and recovery times for the beach and habitats depended largely on availability and proximity to sand supply. El Niño increases in sediment discharge caused an increase in sand supply with updrift beaches recovering much of the beach widths and sand heights by the end of 1998, while downcoast beaches continued to erode for more than six years after the event. Recovery of wrack abundance and shorebirds to pre- El Niño levels took more than 3 years with reductions in the biomass and mean size of invertebrates still detected 2 years after the event.

These physical and ecological responses and recovery timelines of sandy beaches to a major El Niño event have significant implications to coastal managers evaluating shoreline management alternatives and habitat conservation planners tasked with managing ecosystems and restoring habitat.

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Chapter Three

REGIONAL SHORELINE AND BEACH CHANGES IN THE SANTA BARBARA SANDSHED

ABSTRACT

Beach widths and shoreline change along Santa Barbara and Ventura counties, California were evaluated using a 70-year record of rectified historical air photos. The analyses did not reveal any large-scale, long-term beach narrowing that would be associated with a reduction in sand supply caused by dam construction and shoreline armoring. Instead, beach widths oscillated widely across the littoral cell. Updrift of the Santa Barbara harbor, minimum beach widths were closely related to the strong El Niños events of 1982-83 and 1997-98. Downdrift of the harbor, minimum beach widths did not follow this similar El Niño pattern suggesting that the harbor regulated downdrift beach widths. The beach width analyses did reveal a pattern of narrowing attributable to shoreline armoring. Along the seventy kilometers of the study area, 60% (41.9km) of the shoreline is armored and showed accretion of the back beach and erosion of the wet/dry shoreline, patterns consistent with the effects of placement loss and passive erosion. The largest shoreline and beach width changes were a result of the construction of Santa Barbara harbor in 1928.

Beach responses to large El Niño events formed a pattern of beach width reduction by >50% and rotation into the dominant direction of wave attack. Long-term shoreline change patterns show a similar pattern of shoreline reorientation providing evidence that El Niños play an important role in long-term coastal evolution. A large volume of sand (~385,000 m^3) eroded during the 1982-83 El Niño moved downcoast as a pulse, but visible only along stable beaches updrift of the Santa Barbara Harbor. Sand volumes above mean sea level on these stable beaches could not account for the entire eroded volume indicating that portions were transported offshore and alongshore since the entire volume could be accounted for in the Santa Barbara Harbor dredge records as an increase above average annual dredge volumes.

The application of a beach width methodology to regional coastal change analyses provides additional information on sand volumes, beach response to storm events, and the impacts of human alterations to the coast. This information can assist coastal managers in identifying cumulative impacts of shoreline armoring and to quantify impacts to sand supply.

Keywords: littoral cell, beach widths, shoreline reorientation, armoring, shoreline change, passive erosion, placement loss, El Niño, sand pulses

INTRODUCTION

Beaches are significant economic drivers of coastal communities and national economies, supporting commerce, recreation, and ecosystems (Heinz Center 2000, Griggs *et al.* 2005). Economists estimate that without California's beaches the state would lose about $5.5 billion annually in direct spending and the U.S. economy would lose an additional $2.4 billion annually (King and Symes 2004). Beaches also provide hazard protection from coastal erosion which in many places threatens public facilities, infrastructure, and oceanfront property. The response has been an increase in shoreline armoring that has reduced habitat, recreation, and economic opportunities (Griggs *et al.* 2005). Beaches are threatened, trapped between global sea level rise and increasing population growth along the shoreline. Beaches depend on a variety of coastal and watershed processes to maintain sand supply. Human alterations in our watersheds and along our coasts, however, have reduced this supply of sand in some areas and there is a growing urgency to understand the regional impacts of these human alterations.

The Santa Barbara Sandshed (watershed + littoral cell) (Revell *et al.* 2007) extends 245 km from the Santa Maria River in the north, around Point Conception, where the north-south trending U.S. West Coast takes an abrupt turn to a west-east trending shoreline orientation into the Southern California Bight (Figure 1). The sand found on these beaches moves along the coast of southern Santa Barbara and Ventura Counties to the Point Mugu submarine canyon in the south.

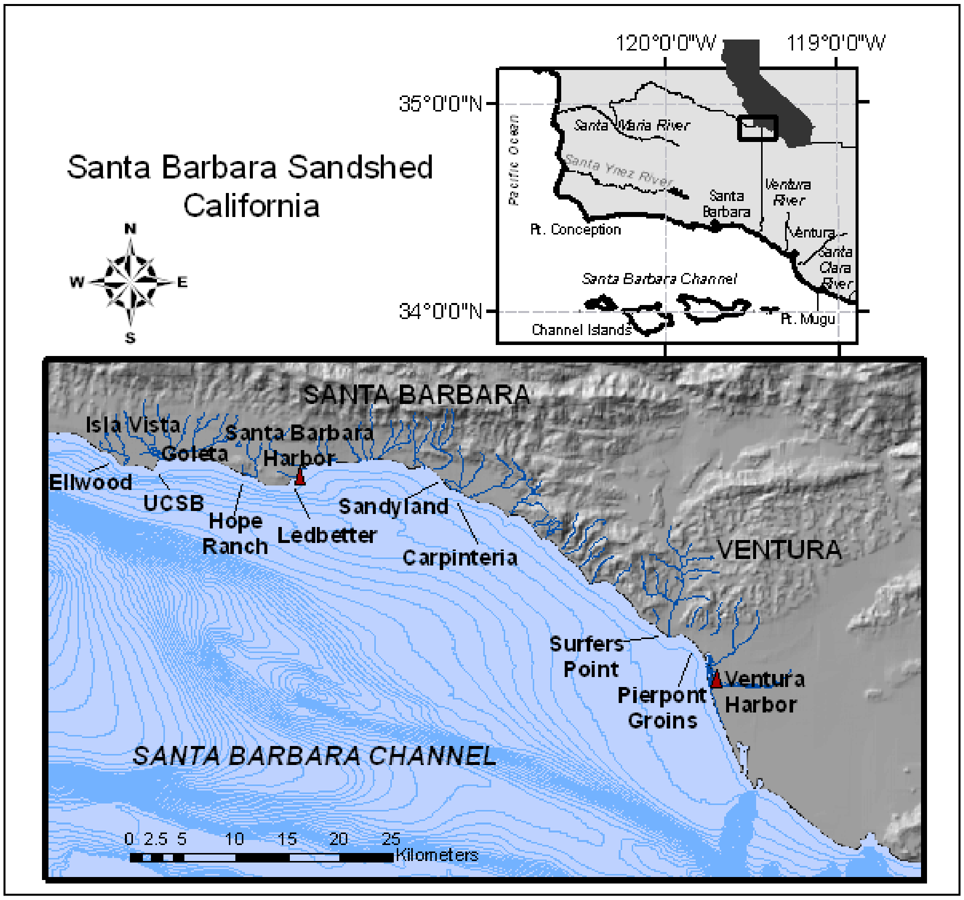

Figure1. The Santa Barbara Sandshed (inset) with zoomed in view of the study area

The Santa Barbara Sandshed is a relatively complex coastline with a variety of rocky outcrops, offshore reefs, and relatively narrow beaches. The beaches receive the majority of their sand inputs from four major rivers: the Santa Maria, Santa Ynez, Ventura, and Santa Clara rivers, which drain the sedimentary rocks of the Transverse Range, along with numerous small coastal drainages that pulse sediment during episodic rain events (Inman & Jenkins 1999) (Figure 1).

Point Conception in the northwest and the Channel Islands to the south, create a narrow swell window that shelters much of the south facing coast of Santa Barbara County from extreme wave events (Figure 1). The Mediterranean climate of southern California results in mild annual temperatures and low precipitation punctuated by episodic and often extreme events frequently associated with El Niños. Winds and wave heights vary seasonally but focusing of waves into the Santa Barbara Channel drive an almost unidirectional longshore sediment transport from west to east in which beaches narrow during the winter and spring (November to April), and widen during the summer and fall (May to October). Longshore transport rates for the study area are approximated by the 70-yr Santa Barbara Harbor dredge record which shows a mean annual rate of ~230,000 m^3 of sand removed per year (Patsch and Griggs 2007) (Figure 2). Variability in the dredge volumes stem from sediment supply, navigational depth requirements and funding. The southern coast of Santa Barbara and Ventura counties are composed mostly of bluff-backed beaches perched on bedrock shore platforms. Along this coast are a few dune-backed beaches that have formed near ephemeral creeks and sloughs, typically controlled by the complex faulting in the Western Transverse Ranges.

This northern end of this sandshed has been characterized as the last remaining stretch of relatively undeveloped coast in southern California. However, this does not

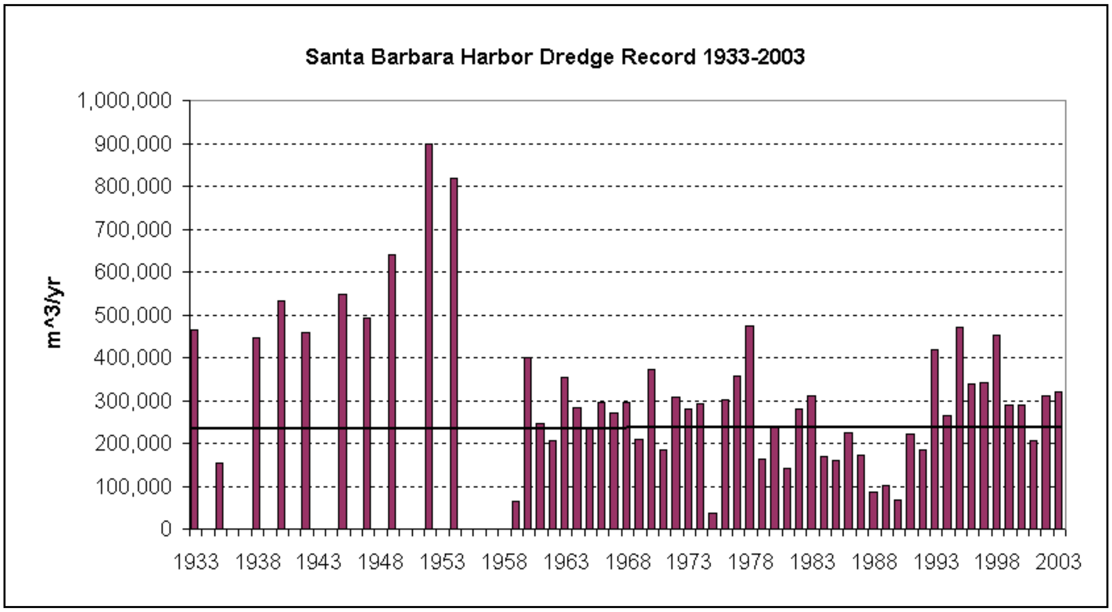

Figure 2: Santa Barbara harbor dredge record 1933-2003. Solid black line is long term mean of 230,000 m^3/yr. Data from Army Corp of Engineers

imply that it is without human influence. Physical alterations to the Santa Barbara coastline began with the completion of the Southern Pacific Railroad in 1901. Physical alterations to the Santa Barbara Sandshed began with dam construction on major rivers: the Santa Ynez River in 1920, the Ventura River in 1955, and on the Santa Clara River in 1948 (Patsch 2004). In 1928, the Santa Barbara Harbor was constructed and began to impounding sand providing a classic example of down coast erosion caused by the disruption of longshore transport (Wiegel 2002). The effects of dam impoundment and shore protection structures on sand delivery to the coast have been quantified in the Santa Barbara cell and show an approximately 40% reduction in sand supplied to the sandshed by the major rivers and bluff erosion, although the great majority of the sand reduction is from stream impoundment (Willis and Griggs

2003, and Runyan and Griggs 2003). It was predicted that this reduction would correspond with a decline of sand volume dredged at the harbors in the cell. Using dredge records as a proxy for littoral drift, Patsch and Griggs determined an average longshore transport of sand at Santa Barbara Harbor since 1933 (~230,000 m^3/year), (Figure 2) and the Ventura Harbor since 1964 (~550,000 m^3/yr) with no sign of reductions in dredge volumes (2007). This paper examined one potential explanation for this lack of reduction in harbor dredge rates that the beaches were narrowing and supplying the sand that had been lost by river impoundment.

This hypothesis was tested along the 10 km Isla Vista coast, updrift of the Santa Barbara Harbor, where it was found that beach widths had not narrowed but instead oscillated (Revell and Griggs 2006). Major beach changes were related to the occurrence of large El Niños, which elevate water levels, wave heights, and precipitation while shifting the normal storm track to the south creating more westerly wave attack in this study area (Seymour 1998, Storlazzi and Griggs 1998, Inman and Jenkins 1999, Storlazzi and Wingfield 2005, Bromirski *et al.* 2005). The oscillations in beach width were found to coincide with different phases of the Pacific Decadal Oscillation (PDO), a climate index of sea surface temperature with a periodicity of ~20+ years (Mantua *et al.* 1997). During positive PDO phases, despite El Niño-like patterns of increased precipitation and stream flow (Inman and Jenkins 1999), beaches narrowed; during negative and calmer, drier PDO phases, beach widths widened (Revell and Griggs 2006). The driving mechanisms of beach changes are most likely related to the change in wave directionality that shifts waves more to the west during large El Niño events (Seymour 1998, Storlazzi and Wingfield 2005). A shift in wave direction over a longer period of time would preferentially affect beaches that were normally sheltered in the Southern California Bight (Graham 2003). This PDO related oscillation has also been observed in Kihei, Maui, where similar sheltered areas were affected by the change in wave direction (Rooney and Fletcher 2005).

The focus of this present study has been to extend the beach width and shoreline change assessment to a 70-km stretch of the Santa Barbara Sandshed extending from Ellwood Beach to Ventura Harbor in order to evaluate the response of beaches and the shoreline to the quantified reduction in sand supply. This study also focuses on the beach response to major El Niños, and human alterations to the coastline.

METHODOLOGY

Historical aerial photographs provide one of the best data sources for long-term shoreline and beach change investigations. Many investigators have utilized various shoreline reference features to examine changes to beaches and shorelines (see Crowell and Leatherman 1999; Boak and Turner 2005 for recent reviews). More recent applications of high accuracy, topographic Lidar data enables a rapid assessment of long stretches of coastline and provides additional information on beach volumes and regional shoreline changes caused by extreme storm events (Revell *et al.* 2002; Sallenger *et al.* 2003).

The use of air photos for accurate shoreline change assessments requires an understanding of potential error sources. Errors inherent in air photo interpretation can be broken down into 1) source error, 2) interpretation error, and 3) short-term natural variability errors (Morton and Speed 1998). Source error results from photo distortion, scale, and scanning errors (Moore 2000). Interpretation errors come from difficulty in locating shoreline reference features. Short-term variability errors arise from seasonal changes in beach profile and variations in water levels and wave run-up elevations that change the location of the shoreline reference features (Morton and Speed 1998, Ruggiero *et al*. 2003)

For this study, eighteen different sets of vertical air photos were obtained for the period from 1929 to 2003 (Table 1). Photographs selected for this study (at scale 1:24,000 or smaller) were taken during the calmer season (summer to fall) to reduce the influence of seasonal variability and to ensure that beaches were near a maximum width. Due to the large study area and strict criteria, only a few photo sets were available with complete coverage (1975, 1989, 1994, 2001).

To minimize errors, historical imagery was rectified using known coordinates of ground locations obtained through GPS surveys to reduce photo distortions (Moore

2000). For each image, two shoreline reference features were digitized - the wet/dry line identified using tonal contrasts, and the back beach or toe of the cliff or dune.

Year	Date	Scale	Isla Vista	Carp-interia	Santa Barbara	Ventura	Spatial Error (m)*
1929	NA	15840		X			9.7
1938	NA	24000	X	X			9.3
1943	9/22/1943	20000	X		X		9.3
1945	11/13/1945	14400				x partial	8.7
1947	8-/20 and 8/21/1947	24000	X	X		X	9.3
1959	11/23/1959	15600	X	X			8.4
1959	8/22and 11/5/1959	16000				x partial	8.4
1966	9/23 and10/18/1966	12000	X	X			8.4
1966	7/5/1966	12000				x partial	8.2
1968	7/22/1968	30000				X	9.2
1969	10/30/1969	12000	X	X			8.3
1971	6/1/1971	12000	X				8.2
1973	8/23/1973	12000	X				8.1
1975	7/29/1975	24000	X	X	X	X	7.2
1981	6/15/1981	24000				X	7.5
1983	10/26/1983	24000	X		X		6.1
1986	10/31/1986	24000	X		X		6.5
1989	5/22 and 5/23/1989	24000	X	X	X	X	6.4
1992	9/1/1992	24000				X	6.6
1994	9/9/1994	24000	X	X	X	X	5.0
2001	9/25/2001	12000	X	X	X	X	6.3
2003	6/25/2003	6000	X	X			5.4

Table 1: Specifications of Aerial Photography. *Spatial Errors are an average error for the entire flightline. Sources –University of California, Santa Barbara Map and Imagery Library; California Coastal Commission, USGS- United States Geological Survey, and Pacific Western Aerial Surveys.

The beach width is the distance between the wet/dry line and the back beach feature, generally the dry sand portion of the beach at the time of the photo. Given the short-term variability of water levels, corrections to the wet/dry proxy- based shoreline reference features were based on the tide level portion of the total water level model discussed in Ruggiero *et al*. (2003). Tide level corrections adjusted the wet/dry shorelines to Mean Sea Level (MSL) (0.829m NAVD88) using historic hourly water level data at Santa Barbara harbor available from NOAA. These corrections translated the water level at the time of each historic photo onto an average summer beach slope calculated from historic profiles and the 1997 lidar data for each shoreline segment. The historical beach profiles were limited in both space and time. Along the 70-km study area, 18 profiles (BEACON #1-18) were available beginning in 1987 and taken intermittenly about every 5 years, with no consideration for seasonal variability. The beach slopes averages used in the tidal correction were taken only from the historical summer profiles (June to Oct.) and ranged from 0.036 (sand beach) to 0.11 (cobble beach). The specific value of the beach slope used in the tide level correction was chosen based on the proximity of the individual transects to the nearest historical beach profile location. Due to the typical low energy waves found in the Santa Barbara Channel during the summer and fall, and the lack of directional hindcast wave data for most of the photography, a wave run-up adjustment was not included in the proxy-based shoreline correction.

Error estimates for the identification and absolute spatial location of the shoreline reference features associated with shoreline change analysis are, +/- 9.7m, and +/- 9.3 m for the early 1929 and 1938 photography, respectively based on a quadrature method. More recent photography scanned at a higher resolution provides lower spatial errors on the order of +/- 7m (Table 1). Errors reported in Table 1 are an average root mean square (RMS) error of all photos in the flight line and relate to the spatial accuracies associated with the reference features. Unlike the shoreline change analysis that depends on different images, the errors in beach width measurements are spatially independent since both reference features can be seen in each image. Maximum potential errors to the beach width corrections associated with choosing one tide level and slope for the entire flight is 10.6 m, assuming a spring tide range (2.3 m) and the most dissipative mean slope (.036 tanβ), a flight time of 1 hour for the 70 km stretch. The tidal records show that none of the photo flights were taken during the maximum spring tide fluctuations although several flights occurred during spring tides making this most likely an overestimate of errors. Beach width errors resulting from the use of a mean summer beach slope for all of the photos was examined by comparing the beach width corrections using the range of historic beach slopes through all seasons. The largest difference in beach width corrections using the minimum versus maximum historic beach slope and the maximum water level adjustment for a given year was 29.2 m. However since the photos were selected from summer and fall, then the use of a mean summer beach slope should reduce the potential errors from the use of a single slope.

To understand the changes caused by the 1997-98 El Niño event, NOAA, NASA, and the USGS partnered to conduct pre- and post- storm Lidar surveys in October 1997 and April 1998 for most of this study area (Sallenger *et al.* 1999). Lidar data was obtained from the NOAA Coastal Service Center and processed to extract a MSL contour. The back beach reference feature was hand digitized using visual cues in cross-shore profiles, slope breaks, and hillshade layers. These two reference features were included in the beach width change analyses, and the 1997 data set was included in the shoreline change analyses.

Shoreline change and beach widths for all imagery were measured along the same 50-meter transects using the USGS Digital Shoreline Analysis System (DSAS) (Thieler, *et al*. 2003). All shoreline change rates and error statistics discussed in this paper were calculated using DSAS version 3.2 (Thieler, *et al*. 2005). For this study, we focus on the shoreline change linear regression (LRR) and end point rates (EPR).

Beach widths were measured for individual years, by setting the back beach reference feature to one year after the date of the wet/dry shoreline so that the EPR calculation actually measured the beach width. Tide corrections were then applied to the beach widths following measurement with DSAS. Beach width measurements and the average beach slopes used in the tide level corrections were multiplied to calculate sand volumes above MSL per transect (m^3/m). Transect volumes were then multiplied by the 50m transect spacing and summed alongshore to provide a total volume for a length of shoreline. A sensitivity analysis examined the difference in beach volumes calculated using the range of beach slopes. The use of maximum and minimum beach slopes in the volume calculation led to maximum differences on wide beaches up to 45 m^3/m.

Beach width changes were calculated by subtracting the older beach widths from the more recent year at each transect (Figure 3). For example, to calculate the long-term changes between 1929 and 2001, the 1929 beach width (e.g. 30m) was subtracted from the 2001 beach width (e.g. 20m) so that any negative change would indicate beach narrowing (e.g. 20m -30m= -10m).

The intersection of the 50m transects and the individual wet/dry shorelines for each year were then used to calculate shoreline orientations. At the intersection points of the wet/dry shoreline and the transect lines a straight line was drawn between transects. An azimuth angle of this intersecting line was calculated in ArcGIS. By adding 90 degrees to this azimuth angle a shore normal or perpendicular angle to the shoreline was created.. (Note: this azimuth angle is not to be confused with the azimuth angle derived by DSAS which calculates the azimuth of the transect line). Shoreline orientations were filtered to exclude all transects in front of shore parallel protection structures, at rocky outcrops and near creek and river mouths to reduce the noise associated with inlet dynamics and abrupt or artificial changes in the shoreline.

RESULTS

Beach Widths

The beach widths in the study area have varied widely throughout the 70-year aerial photographic time series (Figure 1). Two types of beaches can be identified - stable beaches and storage beaches. A stable beach maintains a wide minimum beach width and a storage beach is one that exhibits extreme natural variability but has zero minimum beach width. Stable beaches (e.g. Ellwood, Hope Ranch and Carpinteria) provide good locations to examine storm impacts, and to observe pulses of sand moving along the coast. A storage beaches demonstrate a capacity to store sand and may make better locations for potential nourishment projects. An example of a storage beach is UCSB, a beach that reached maximum widths (>150m) in the 1960s and 1970s (Revell and Griggs 2006), but has also been completely removed at times.

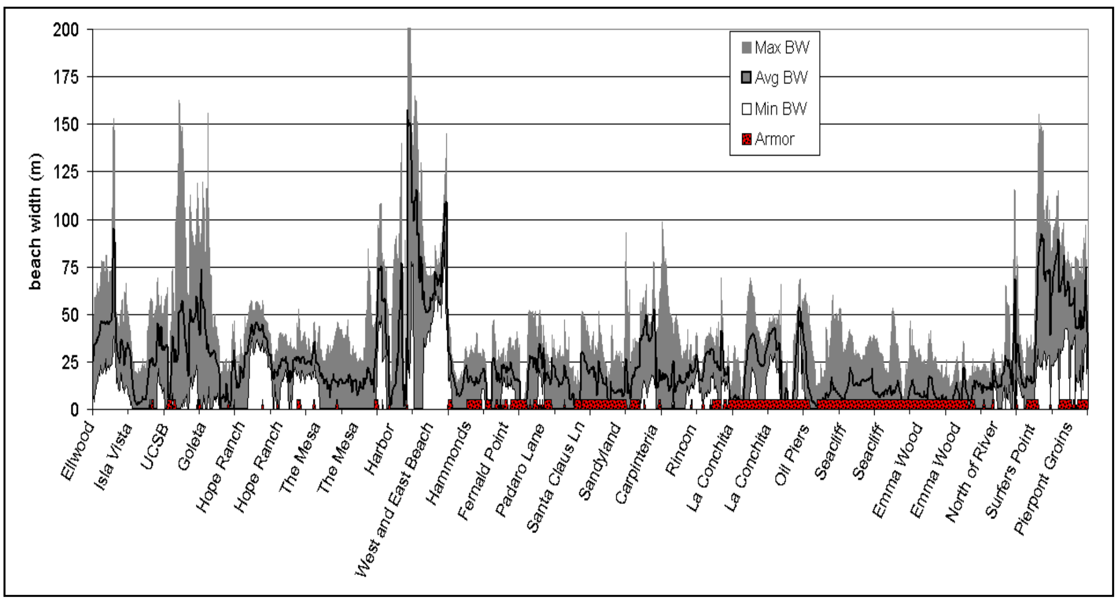

Figure 3. Beach width variability along 70 km of southern Santa Barbara and Ventura Counties throughout all of the available years of aerial photography 1929-2003.

This result from Figure 3 divides the study area into two parts based on the location relative to the Santa Barbara Harbor. The updrift beaches to the west of the Harbor (toward Ellwood) face more southward and exhibit a wider range of beach widths with minimum widths following either the 1982-83 or 1997-98 El Niño. The maximum widths for these beaches were reached mostly in the 1970s. Current beach widths are similar to those found in the 1940 for most of this part of the study area.

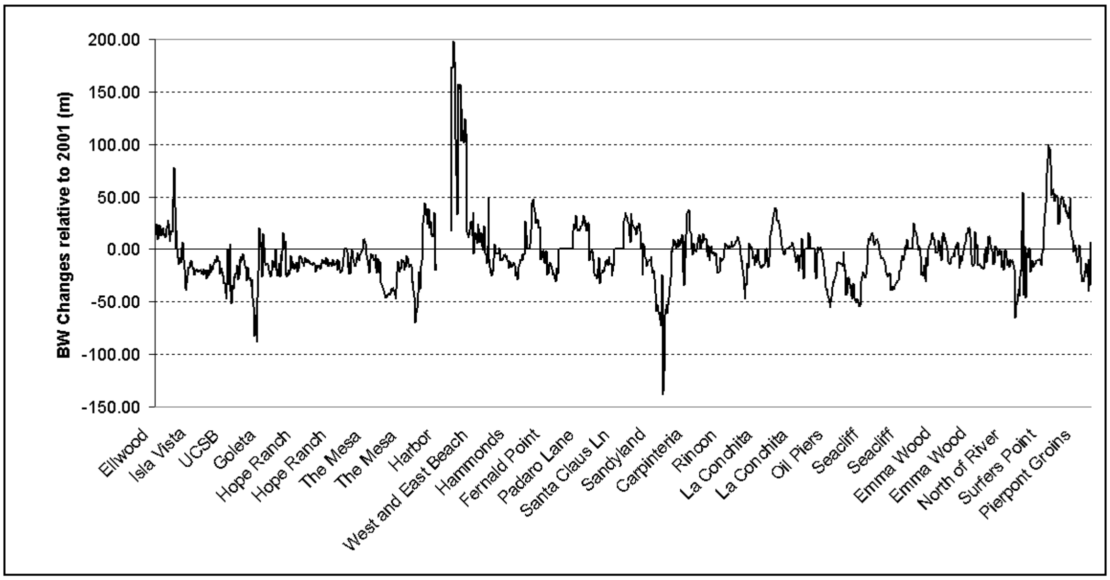

Figure 4. Long-term beach width changes relative to the 2001 beach width. The earliest dates used in the calculation vary based on air photo availability. (1943 updrift of the Santa Barbara harbor and 1947 downdrift of the harbor, with the exception of 1929 for Carpinteria. A negative beach width change indicates that the beach has narrowed, while a positive change indicates accretion.

The beaches downdrift of the harbor (toward Carpinteria and Pierpont groins) have smaller ranges of beach widths and are primarily armored shorelines (Figure 1). The minimum widths do not follow El Niño events and maximum widths along this stretch do not fit any obvious pattern, although the lack of photo sets available prior to railroad completion in 1901 (we didn't have airplanes yet for aerial photos), extensive armoring, and highway expansion limit the analysis.

One primary research objective is to examine the long-term changes in beach widths to ascertain whether the beaches have narrowed over time, and in doing so would have supplied sand to the harbor dredge records and thereby compensated for the reduction in fluvial sand supply (Willis and Griggs 2003, Runyan and Griggs 2003). Figure 4 shows long-term beach width changes relative to the 2001 beach widths. Overall, there is not a uniform narrowing of beach widths across the study area. The average beach has widened by ~4m with beach width variability shown in the 33 m standard deviation. However, the beaches updrift of the harbor from Isla Vista east to the harbor (excluding Ellwood and the beach immediately updrift of the Santa Barbara harbor), show an average narrowing of ~18 meters between 1943 and 2001.

The largest beach width changes in this study area result from transportation and engineering projects. The greatest widening and narrowing both resulted from the construction of the Santa Barbara Harbor in 1928. West Beach, immediately downdrift of the sand bypass widening by ~200m, while Carpinteria showed the greatest beach narrowing (-138 m). Other large beach widening (>75m) has occurred at the Pierpont groins in Ventura and at Ellwood Beach. Ellwood Beach is uniquely situated, facing west into the dominant wave direction, and is the only natural dune-backed shoreline remaining in the study area. Large beach narrowing has occurred at

Goleta Beach (-88 m) as a result of the construction of the Santa Barbara airport and the loss of tidal prism at Goleta Slough (Revell and Griggs 2006). It is important to note that this end point beach width change analysis does not capture the oscillations in beach width that have been previously documented (Revell and Griggs 2006).

Beach Widths and Shoreline Orientation

Due to the irregular shape of the coastline and the near uniform wave direction, wave exposure varies greatly depending on shoreline orientation. Oscillations observed in the long-term beach change width analysis (Figure 4) are related to changes in the shoreline orientations that partially control beach widths due to exposure to wave attack (Figure 5). The shoreline orientation results indicate that the most stable and widest beaches are those found facing SSW (255° to 210°, and SSE (165°-150°). The narrowest beaches are found facing close to south (210°-165°), with the exception of the beach created at the end of the Santa Barbara Harbor dredge discharge site (180°).

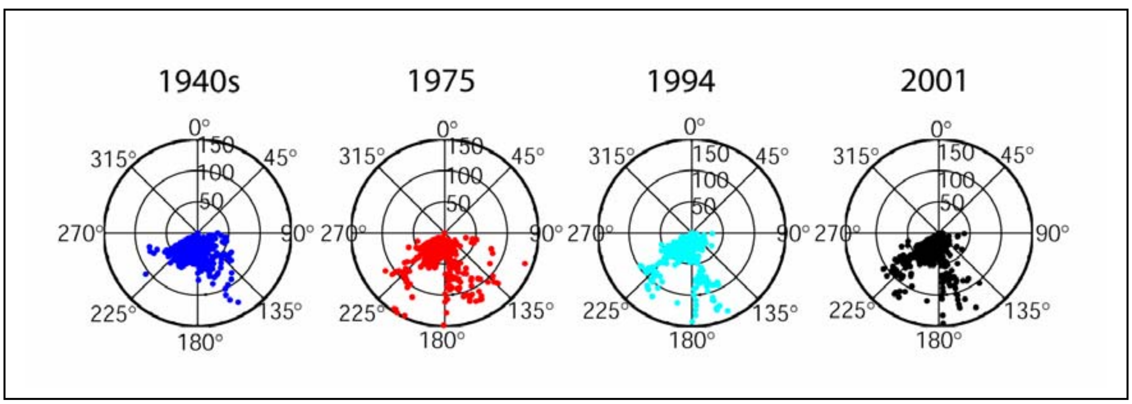

Figure 5. Beach Widths plotted by shoreline orientation for separate years. Data points were extracted from the same shoreline transects and have comparable number of data points. Radial axis is beach widths in meters.

The shoreline orientation analysis also demonstrates the impacts of cross-shore littoral barriers (e.g. groins, jetties) across the study area through time.

While air photo data from the pre-harbor construction era are sparse, it appears from historic oblique photos that most of the beaches were relatively narrow. In the 1940s (data from 1943 for area west of harbor, and for 1947 east of harbor), the beaches remained relatively narrow with the widest being in the east (165°-150°) as a result of Santa Barbara Harbor construction and the trapping of sand to form the updrift Ledbetter Beach. The wide beaches in the west were found in the dunes of Ellwood Beach (255°-235°). By 1975, a series of engineered groins were constructed at Pierpont creating wide beaches near Ventura (225°- 215). The beaches in 1975 were generally wide, and the SE facing UCSB storage beach (105°-120°) reached its widest width. After the 1982-83 El Niño, the wide beach at UCSB was eroded (~100m) (Revell and Griggs 2006). Throughout 1994 and 2001, beach widths continued to widen from the 1982-83 El Niño. Despite the large 1997-98 El Niño, most of the beaches were relatively wide in 2001.

Shoreline Change

Change rates were calculated for both the wet/dry shoreline proxy and the back beach reference feature at each transect along the entire study area (Table 2, Figure 6). The change rates summarized in Table 2 do little to describe the smaller spatial patterns

Shoreline Change	Average (m/yr)	Maximum (m/yr)	Minimum (m/yr)
LRR_Back Beach	0.07	3.13	-1.59
LRR_Wet/Dry	-0.01	2.81	-2.37

Table 2: Shoreline Change Rates; LRR – linear regression rate

and trends associated with the different shoreline segments (Figure 6). However, when averaged over the entire study area, change rates calculated using linear regression (LRR) show a reversal in trend between the wet/dry shoreline and the back beach. The differences between the back beach and the wet/dry shoreline can be

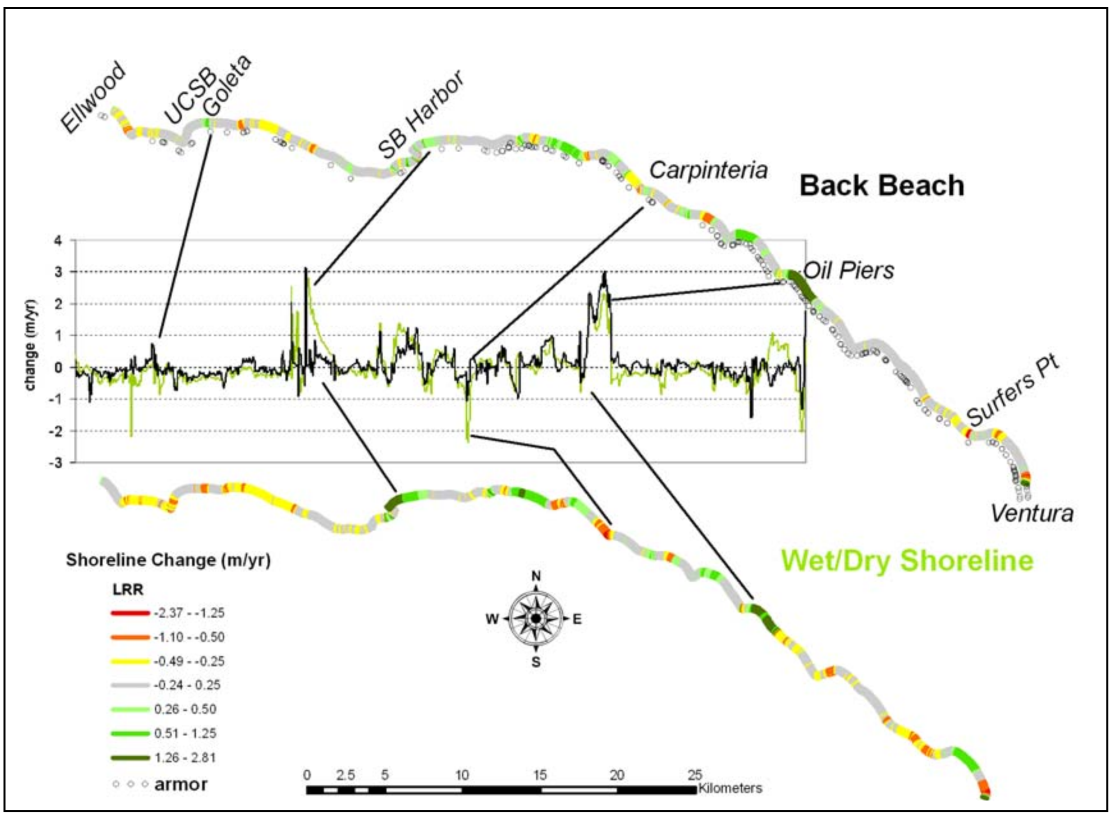

Figure 6. Shoreline change rates (linear regression) for both the wet/dry and back beach shorelines.

attributed primarily to the presence of shoreline armoring. Along an unarmored beach, given a steady supply of sand, widths should stay relatively stable over the long-term, with the beach migrating landward or seaward depending on changes in sea level. In this case, shoreline change rates for both reference features should be similar. However, once the back beach is armored, then the back beach feature accretes due to placement loss (determined by the footprint of the structure). As sea level rises, the wet/dry shoreline continues to retreat and passive erosion occurs.

Over the entire study area, the largest erosion rates of both reference features detected using LRR occur at UCSB Beach, and at the inlet to Carpinteria Salt Marsh with both rates greater than –2 m/year (Figure 6). Maximum accretion rates are a direct result of engineered structures, the construction of the Santa Barbara Harbor and the construction of the oil processing facilities at Oil Piers resulted in 70-year shoreline change rates of ~3m/yr (Figure 6). While these analyses may facilitate regional sediment management (e.g. nourishment locations) and a better understanding of cumulative impacts (e.g habitat loss, placement loss), most of the decisions directly affecting long-term beach widths (e.g. setbacks, flood control) and recreational and economic opportunities happen at a much smaller scale.

Case Study: Carpinteria Erosion

Breakwater construction and sand impoundment at the Santa Barbara Harbor led to a well documented erosion wave that migrated downcoast at ~1.7km/yr (~1mi/yr)

(Komar 1998, Weigel 2002 among many others) (Figure 7). While the reporting of this erosion wave is not new, the application of a beach width methodology to study this erosion event provides new information on the response of the beach and shoreline (Figure 8). Figure 8a shows the changes to the beach following the erosion wave determined by subtracting the beach widths between 1929-1938. While beach

Figure 7. Photo taken 1936 after the erosion wave had passed Fernald Point en route to Carpinteria. Santa Barbara Harbor visible in the distance, note the extent of cross-shore groins in place to slow erosion.

widths were largely eroded in the west (-150 m), there was also widening of the beach at the east end of the shoreline segment (~55m) (past the creek mouth located at transect 792) resulting in a change of the shoreline orientation. The beach has maintained this alignment for the subsequent 63 years (1938-2001), although the center of the beach widened some 50 meters over the longer time period for a near zero change in beach width since the erosion wave arrived.

In Figure 8b, the wet/dry shoreline change analyses shows a similar pattern of reorientation as the beach width changes. However, the back beach change rate at the west end of the beach (transects 760-770) shows an accretion trend caused by the construction and encroachment of a revetment onto the beach. While the accretion

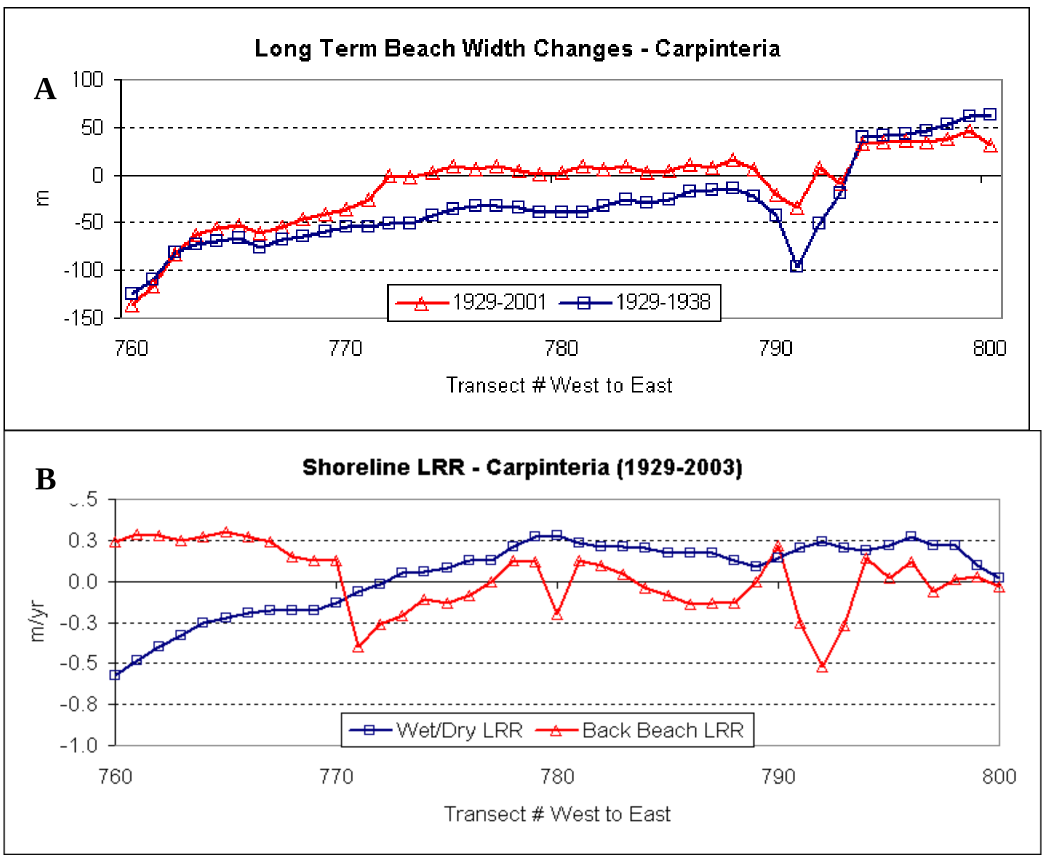

Figure 8. (a) Beach width changes and (b) shoreline change rates compared at Carpinteria. Note that Carpinteria Creek outlets between transects 791-793.

“rate” of the back beach is not valid after a structure is built, the reversal in shoreline change rate identifies this human alteration. The shoreline change immediately adjacent to the revetment along the city beach (transects 770-780) follows the overall pattern of reorientation shown in the wet/dry shoreline change rates.

The lidar and air photo derived beach widths were combined to examine the response and recovery of the beaches at Carpinteria to the large El Niño events of 1982-83 and 1997-98 (Figure 9). The 1982-83 El Niño was the largest El Niño on record and had

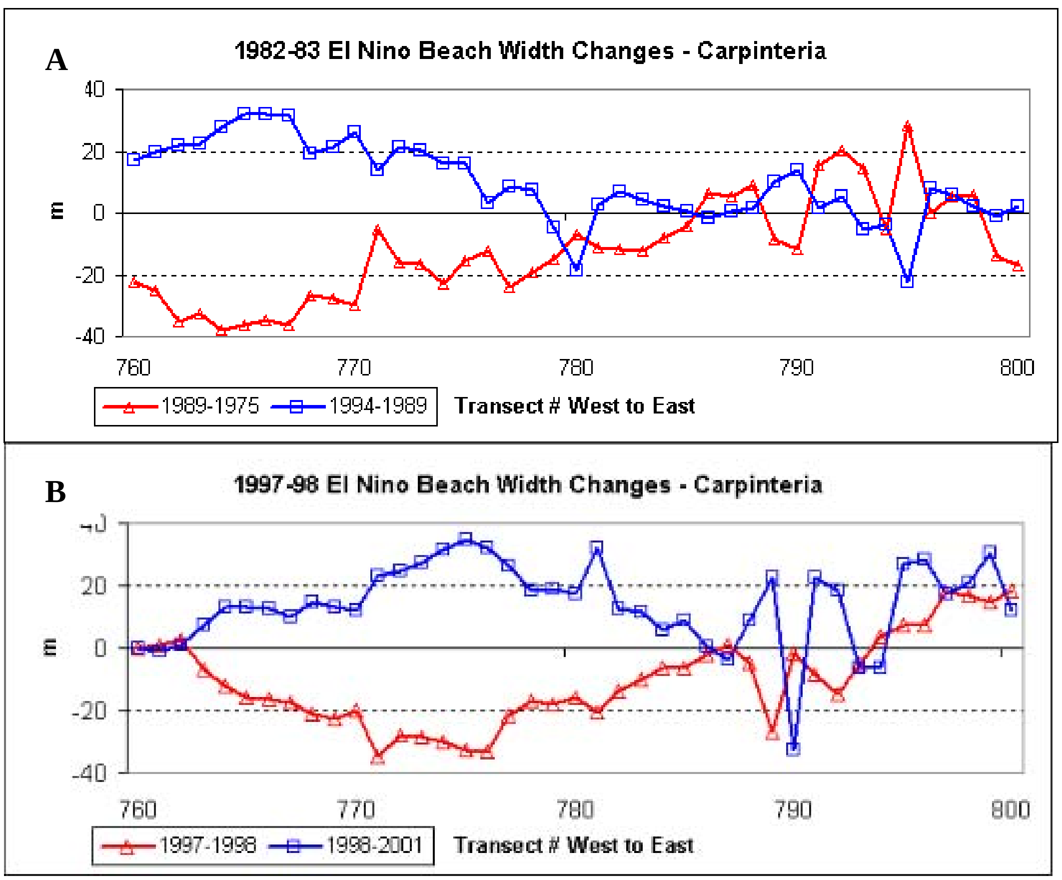

Figure. 9. Beach width changes and recovery following the (a) 1982-83 and (b) 1997-98 El Niños.

devastating impacts to several beaches in the study area (Revell and Griggs 2006). In Carpinteria, due to the lack of available air photos, the closest available photo sets bracketing the event were taken in 1975 and 1989 (Figure 9a).

The beach width changes were analyzed using these photos revealing the same El Niño pattern of beach reorientation characterized by nearly 40m of narrowing in the west end and ~20m of beach widening near the east end. By 1994, the next available photo set, this reorientation had recovered to the preexisting 1975 state.

Following the 1982-83 El Niño, a revetment was constructed from upcoast to transect 770 to protect the structures near the erosion hotspot seen in Figure 9a.

Examination of the lidar beach widths of 1998 and 1997, revealed a similar pattern to the long-term beach width and wet/dry shoreline reorientation (Figure 9b). Narrowing near the west end of the beach of ~40m was conversely related to east end widening of ~20m. The recovery of the beach at the west end was complete by the time of the subsequent available air photo set in 2001 when the west end beach widths accreted nearly 40 meters. The net result by 2001 was that the beach had widened at the east end an additional ~20 meters from the 1998 survey. One interesting note is that the location of the maximum erosion shifted to the east approximately 500m between these two time periods (from Transect 767 to 777). Following the placement loss associated with the construction of the revetment, the beach widths narrowed and the amount of beach width available to respond to the 1997-98 El Niño was reduced. This revetment shifted the erosion hotspot downdrift.

While this pattern of shoreline reorientation is visible in beach response to both major El Niños and in the 70-year long-term shoreline change data, there are several complicating factors in Carpinteria associated with the erosion wave due to harbor construction, the ongoing dredging, and the shoreline armoring. These complications require us to examine another beach to assess this El Niño pattern of shoreline reorientation.

Case Study: Hope Ranch

To better understand these reorientation patterns of shoreline changes and storm responses, it seemed useful to examine a less altered beach. Hope Ranch is a stable, bluff-backed beach downdrift of Isla Vista and Goleta Beaches and updrift of the Santa Barbara Harbor (Figure 1). It can be characterized as having a relatively narrow range of beach widths (~25m), and is notable for its lack of shoreline armoring (Figure 2). This beach provides insight into patterns of long-term and storm changes, as well as sediment transport along this coast (Figure 10, 11).

The 70-year long-term shoreline change of both the wet/dry and back beach shoreline show similar patterns to the Carpinteria wet/dry LRR of increased erosion rates at the west end and smaller erosion rates at the east end (Figure 10a). This erosion rate pattern results in a subtle reorientation of the coast, similar to the pattern seen in Carpinteria (Figure 8a). At Hope Ranch, given the lack of armoring both the

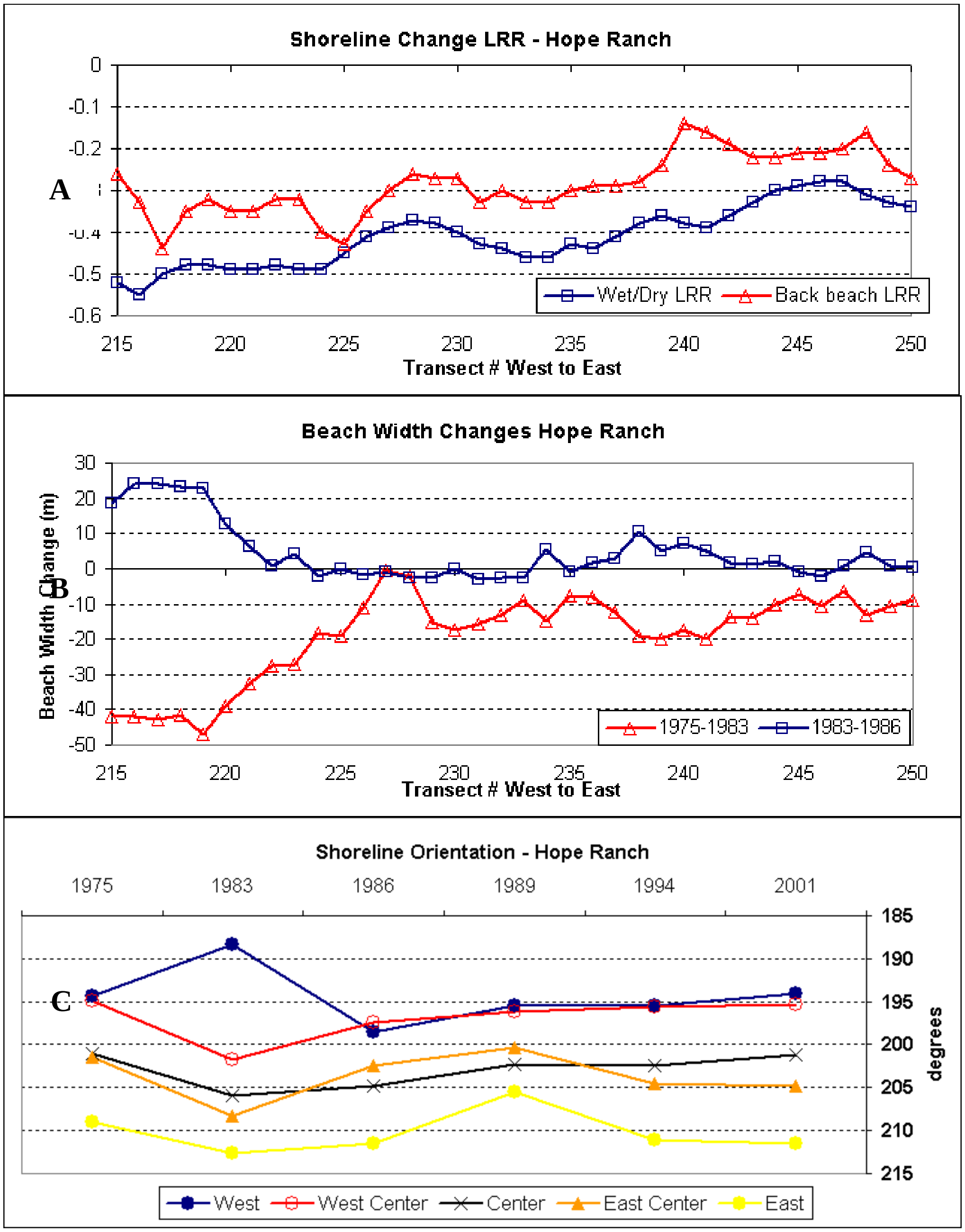

Fig. 10. Shoreline change (a), beach response to the 1982-83 El Niño (b), and (c) shoreline orientation response to the 1982-83 El Niño.

back beach and wet/dry shoreline show similar reorientation patterns with the back beach rates slightly smaller. The Hope Ranch beach response to the 1982-83 El Niño was also similar with erosion at the west end of nearly 50m, and much less erosion seen in the east end (~10m) (Figure 10b). The shoreline orientation data also show the response of the shoreline and the subsequent recovery (Figure 10c). Immediately following the storm event, the 1983 shoreline orientations all rotated to the west except for the western most which rotated eastward indicating the erosion which occurred at the west end. The similarity of this shoreline change and beach response without the complicating factors of harbor influences and shoreline armoring provides evidence that large storm events, particularly those associated with strong El Niños may be playing a major role in shaping the beaches of the Santa Barbara coast.

Sand Transport

To understand how sand is transported along the Santa Barbara coast, the pulse of sand eroded from UCSB during the El Niño of 1982-83 was examined. This erosion event reduced the beach widths at UCSB by ~75 m and the volume of sand by ~385,000 m^3 [-109 m^3/m] (Revell and Griggs 2006). Harbor dredge records show a increase in volume of dredged material above long-term average rates (~230,000 m^3/yr) between 1993-95 that is of the same magnitude as that eroded from UCSB and Goleta Beaches. Given the unidirectional longshore transport, and estimates for migration rates of sand pulses and erosion waves of ~1.7 km/year (~1 mile/year); then this sand would have to be transported downcoast along the Hope Ranch (~7km) and

Ledbetter Beaches (~14km) before being recorded in the Santa Barbara Harbor dredge records. By examining the transport of this sand volume at each transect and the total volumes for the two stable beaches along this relatively unaltered coastline, we can better understand the transport dynamics (Figure 11).

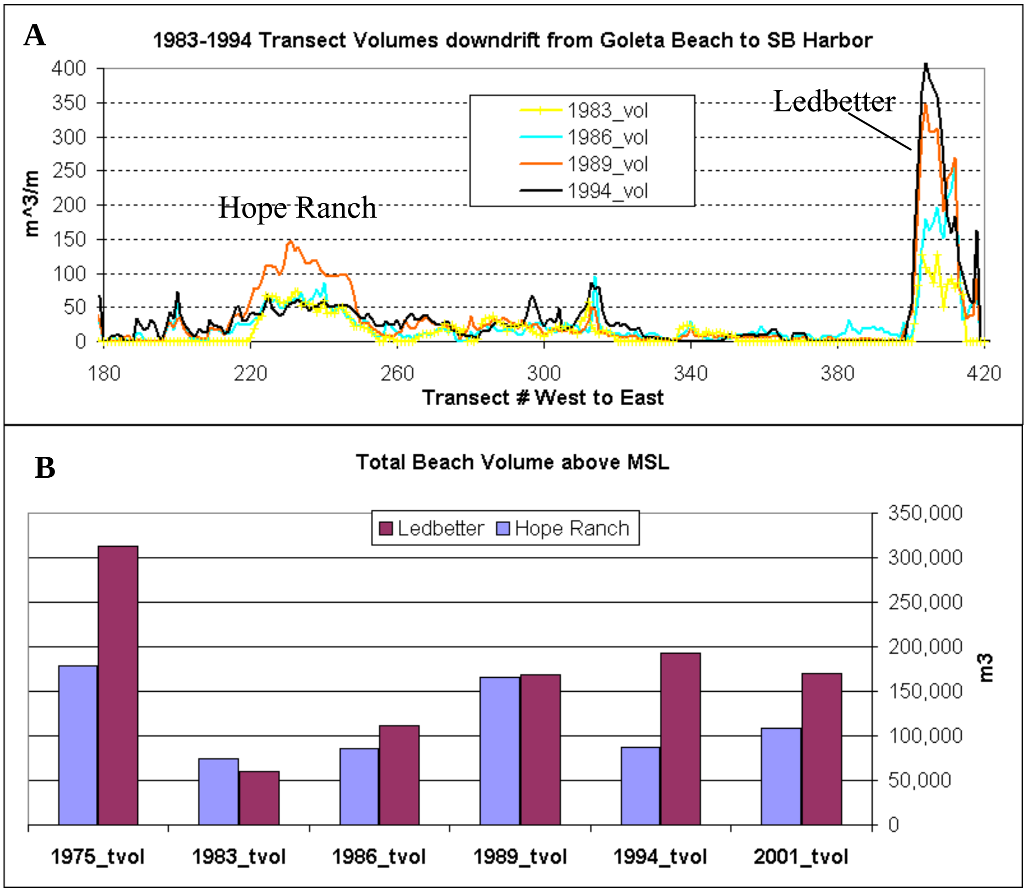

Fig. 11. Transect volume (a) and total beach volume (b) above MSL from Goleta Beach to Santa Barbara harbor following the 1982-83 erosion event at UCSB and Goleta beaches.

Immediately following the 1982-83 El Niño, beach widths and volumes along this segment of coast were significantly reduced. The initial recovery period between 1983 and 1986 resulted in some recovery of the storm reorientation (Figure 10c), but it did not significantly increase sand volumes (Figure 11). By 1989, however, there was a significant beach accretion at Hope Ranch and a counter-rotation detectable at the eastern end of the beach that coincided with the expected arrival time of the sand pulse from UCSB and Goleta beaches (Figures 10c, 11a). At Ledbetter Beach, the sand volume seen at Hope Ranch in 1975 most likely arrived in 1989. By 1994, the pulse of sand had passed Hope Ranch and the eastern end of the beach rotated westward. Meanwhile downcoast at Ledbetter Beach, the beach volumes that had been increasing steadily since the 1982-83 event, reached their maximum at over 400 m^3/m. While the stable beaches at Hope Ranch and Ledbetter show oscillations in beach volume, the beaches in between show relatively little change during the migration of this sand pulse.

Considering that the beaches between Hope Ranch and Ledbetter did not accrete significantly, we can examine the total beach volumes above MSL for these two beaches to try to detect the sand pulse (Figure 11b). The pulse can be seen moving on the beach at Hope Ranch in 1989, which then decreases in width by 1994, while Ledbetter continues to accumulate sand on the beach until 1994. The sand volumes at both beaches are about equal in 1989, evidence that the sand at Hope Ranch pre-1982-83 El Niño migrated downdrift to Ledbetter beach. The magnitudes of beach volumes above MSL at Hope Ranch and Ledbetter and the magnitude of sand lost from UCSB beach and Goleta beaches (~385,000 m^3) are different. Since the beaches between the two beaches did not accrete significantly, the implication is that some of the sand was deposited offshore and moved alongshore below MSL.

DISCUSSION

Beach widths

Beach width methodology when used in conjunction with shoreline change analyses provides information on the shape of the beach, response of the beach to storm events, and additional information for assessing changes in beach volumes. The motivation for selecting a beach width methodology was to determine if there was a long-term narrowing of the beaches that could explain the discrepancy between a sediment supply reduction (Willis and Griggs 2003, Runyan and Griggs 2003) and a steady long-term average dredge volume recorded at Santa Barbara harbor (Runyan and Griggs 2002). The endpoint beach width change analyses did not identify any systematic long-term narrowing that could be attributable to sediment supply reductions. Because the harbor plays a role in regulating beach widths downcoast, we would not expect to see a narrowing unless first finding one in the harbor dredge records. The endpoint analyses on beaches immediately upcoast from the harbor shows some beach narrowing (~18 m). An endpoint analyses is susceptible to influences from extremely wide or narrow beach widths at either one of the two reference points in time and it is quite likely that the photo sets occurred between normal oscillations. Due to the prevalence of narrow beaches with widths near zero, then such a narrowing would best be detected at stable beaches. There is also some evidence of beach width narrowing occurring at Hope Ranch, where long-term shoreline change rates differed between the back beach and wet/dry shorelines. This pattern is consistent with a long-term narrowing of the beach.

The limited findings supporting a beach narrowing updrift of the harbor remain questionable due to the reductions being only slightly larger than the beach width errors +/- 5m. These regional analyses were complicated by the multiple dates and availability of sets of early air photos (ranging from 1929, 1938, 1943, and 1947). Further complicating the analyses was the beach changes associated with a variety of human alterations that pre-dated air photos. Ideally, an air photo set taken during the late summer at lower tide prior to railroad construction (circa 1900), and a pre- harbor 1928 set would be compared to the existing photo sets to better examine this question of long-term narrowing. The use of historic T-sheets is not applicable due to the lack of back beach delineated in the maps and the artistic license in the 1870s maps.

The use of shoreline orientation data helps in the understanding of beach stability, human alterations, and the response of beaches to storm events. More research is needed to understand long-term changes to shoreline orientation of both the wet/dry shoreline and the back beach to determine, whether changes are driven by single catastrophic events, such as an erosion wave or tsunamis (e.g. 1812), or driven by repeated extreme events such as large El Niños or hurricanes (e.g. 1939). Differences in orientation between the two reference features may also provide some information on the stability of the beach but further research is needed.

Human Alterations

While the long-term beach width change analysis did not reveal any systematic long-term narrowing attributable to sediment supply reductions, the analysis did reveal a pattern of beach narrowing attributable to shoreline armoring. Along the seventy kilometers of the study area, 60% (41.9km) of the shoreline was armored with a variety of revetments and seawalls. Along these armored sections, accretion of the back beach and erosion of the wet/dry shoreline illustrate the effects of placement loss and passive erosion. These two effects dominate the large- scale pattern of beach width changes. Another ten kilometers (14.3%) is altered by groins, breakwaters, or other littoral barriers and showed an accretion of the wet/dry shoreline and a relatively stable back beach. With the high rates of littoral transport, the cross-shore structures perform well at building up beach widths, while shore parallel structures have resulted in placement loss, passive erosion, and he net result of reducing beach widths. Once a structure fixes the back beach and the placement loss occurs, then any rate of back beach shoreline changes becomes irrelevant, but the beach width methodology serves as a potential tool for coastal managers for quantifying and assessing cumulative impacts of shoreline armoring over a broad spatial scale.

At smaller spatial scales, differences found between accretion of the back beach and erosion of the wet/dry shoreline could be used to identify locations of placement loss and passive erosion while changes between years during which shoreline armoring has been emplaced could be used to examine active erosion and the location of erosion hot spots. The construction of the revetment along Carpinteria following the 1982-83 event and the similar pattern of erosion in 1997-98 that was farther down coast may be evidence that active erosion and flanking erosion is occurring at the end of the structure, but more research is needed to measure acceleration of processes in front of the structure.

Beach width envelopes (minimum and maximums) helped to identify locations of stable beaches-those with greater minimum widths, and storage beaches- those that exhibit extreme natural variability in widths and could potentially be good sites for beach nourishment. Stable beaches were critical to identify because they provide natural control beaches to examine sediment transport dynamics along the coastline as well as the coastal response to storm events. Minimum beach widths showed a distinct difference between beaches updrift of the Santa Barbara Harbor and those downdrift. Updrift beaches were narrowest following the major El Niños of 1982-83 and 1997-98 while downdrift beaches did not exhibit the same tendencies. While this may partially be explained by the available photo coverage, the implication is that the Santa Barbara harbor regulates beaches downdrift much like a dam regulates river levels downstream.

Storm Event Responses

Beach width responses to large El Niños match the long-term shoreline change patterns of shoreline reorientation at both Carpinteria and Hope Ranch beaches. The air photo coverage for the 1982-83 event at both beaches was not ideal and several years removed from the actual event, but the similarity in patterns between beaches and between El Niño events is striking. If the pattern at Carpinteria observed in 1989 is truly remnant from the 1982-83 event, then the implication is that the 1982-83 event had a longer lasting impact on the coast than the 1997-98 event. The similarity in beach responses along these west facing beaches to both events hints at a predictable pattern of El Niño storm response in which beach widths are reduced by >50% and that beaches rotate clockwise. This knowledge could be useful to coastal managers and emergency responders deciding on how long or where to permit emergency structures, build sand berms or nourish beaches.

Sediment Transport

While several authors have identified large alongshore transport rates, the physical response of the beaches during this transport has been uncertain. The erosion of a large sand volume from UCSB and Goleta Beaches following the 1982-83 El Niño provided an opportunity to examine this transport. The beach volume changes and the pulse of sand observed in progression at both Hope Ranch and Ledbetter beaches indicate that sand travels as a relatively cohesive pulse (Hicks 1985), but that the pulse is only detectable at those stable beaches and not the entire length of shoreline. This may be related to the gradients in longshore transport, or the shoreline orientation. The volume of sand lost from UCSB and Goleta can be accounted for in the dredge records at Santa Barbara (Figure 2) but cannot be entirely accounted for in the beach volumes (above MSL) between these sites, indicating that there is a significant portion of alongshore transport that must occur offshore.

CONCLUSIONS

A 70 year record of beach width changes in the Santa Barbara Sandshed does not reveal any long-term beach narrowing that was hypothesized to be associated with a reduction in sand supply from human alterations. Instead, beach widths oscillated widely across the study area. Updrift of the Santa Barbara harbor, minimum beach widths were closely related to the strong El Niños events of 1982-83 and 1997-98. Downdrift of the harbor, beach widths did not follow the similar El Niño pattern, implying that the harbor was regulating beach widths downdrift similar to a dam regulating water levels downstream.

Overall, the greatest changes to the shoreline resulted from large erosion events, either the 1982-83 El Niño, or the erosion wave associated with sand impoundment and the Santa Barbara Harbor construction. The greatest narrowing of beach widths occurred at 1) Carpinteria- caused by sand impoundment by the construction of the Santa Barbara harbor, and 2), Goleta Beach- due to the construction of the Santa

Barbara airport and the loss of tidal prism at Goleta Slough. The greatest widening of beach widths occurred immediately updrift of the harbor (>200m) as a result of sand impoundment by the breakwater, and from the groin field at Ventura that widened the beach widths by >100m.

While the historic beach width changes did not identify any systematic long-term narrowing attributable to sediment supply reductions, the analyses did reveal a pattern of beach narrowing attributable to shoreline armoring. Along the seventy kilometers of the study area, 60% (41.9km) of the shoreline has been armored with a variety of revetments and seawalls. Along these armored sections, accretion of the back beach and erosion of the wet/dry shoreline illustrate the effects of placement loss and passive erosion. These dominate the large-scale patterns of beach width changes. An additional ten kilometers (14.3%) of shoreline has been altered by groins, breakwaters, or other littoral barriers and showed an accretion of the wet/dry shoreline and a relatively stable back beach.

Assessing the beach width envelopes identified stable beaches, those with a wide minimum width, and storage beaches, those with the highest width variability, indicating a capacity to potentially store sand. Storage beaches may be related to the Analyses of beach widths and shoreline orientation demonstrate that the west facing beaches of Ellwood (255°-240°) were naturally the most stable, with beach widths ranging from 25 to 75 meters. The east facing beaches (120°-105°) were naturally the most variable, ranging from 0 to 150m in width. South facing beaches were the narrowest. Beach width responses to large El Niños events match patterns of long-term shoreline reorientation. The similarity of this beach reorientation pattern in both 1982-83 and 1997-98 El Niños and the long-term change rates provide evidence that extreme El Niños events play an important role in large-scale, long-term coastal evolution.

A large volume of sand (~385,000 m^3) eroded during the 1982-83 El Niño, was transported as a cohesive pulse detectable along the stable beaches updrift from the Santa Barbara Harbor. Beaches between the stable beaches did not show evidence of this sand pulse. The stable beaches (above MSL) updrift of the harbor could not account for the entire eroded beach volume indicating that some of the alongshore transport occurred offshore. The sand pulse was recorded in the harbor dredge records as a significant increase above average dredge rates and match estimates of 1.7 km/yr or ~1 mile/year sand pulse migration rates.

The application of a beach width methodology can be used to detect beach response to El Niño events as well as placement loss and passive erosion. This method can assist coastal managers in responding to large storm events and in quantifying and assessing cumulative impacts of shoreline armoring over a broad spatial scale.

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Chapter Four

SANDSHED MANAGEMENT

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ABSTRACT

Sandshed management links the well-known concept of watershed management with a regional approach to shoreline management that emphasizes the maintenance of a sandy beach to provide hazard protection while preserving recreational, ecological, and economic benefits. Sandshed management planning is described as a three step – inventory, analysis, and implementation process. The inventory is comprised of a collection of cultural characteristics such as economic, social and environmental assets, jurisdictional boundaries, shoreline uses and activities, as well as the physical processes that operate across a range of time and space scales to affect shoreline stability. Delineation of the sediment budget, the balance between sources and sinks within a sandshed, is a key part of the physical inventory. The analysis step includes both an assessment of the cause and extent of inundation and erosion-related hazards, and an evaluation of a range of potentially applicable management measures.

Describing the positive and negative impacts associated with potential management measures in a way that accounts for community values and priorities is a key part of the analysis process. Once a preferred alternative or suite of alternatives has been identified, a range of implementation mechanisms needs to be established. These may include memoranda of understanding or letters of agreement between agencies and organizations, or more formal measures such as the adoption of planning and/or zoning code provisions. The comprehensive, regional approach embodied in the concept of sandshed management has significant implications to the management of our coasts worldwide.

KEYWORDS: regional sediment management, littoral cell planning, coastal hazards, sediment budget, watershed planning, ecosystem-based management.

INTRODUCTION

Beaches are significant economic drivers of coastal communities and national economies, supporting commerce, recreation, and ecosystems (HEINZ CENTER 2000, GRIGGS et al. 2005). Economists estimate that without California's beaches the state would lose about $5.5 billion annually in direct spending and the U.S. economy would lose an additional $2.4 billion annually (KING and SYMES 2004). Beaches also provide hazard protection; it is estimated that over the next 55 years, 1 of 4 houses within 150m of the shoreline will be claimed by erosion (HEINZ CENTER 2000).

Beaches are endangered, trapped between accelerating sea level rise and the continued migration of people to the coast (HEINZ CENTER 2000, IPCC 2001, GRIGGS et al. 2005). In crowded urban areas, beaches remain some of the last open spaces. Sea level rise will exacerbate erosion by exposing coastlines to elevated water levels more frequently.

Coastal processes are largely responsible for the creation and maintenance of beaches. When humans get in the way of these processes, the processes become hazards. A variety of human activities have exacerbated hazards by reducing sand supply to the coast (KONDOLF 1997, WILLIS and GRIGGS 2003, RENWICK et al. 2005). In recent decades, as the demand and price of ocean view and beachfront lands have escalated, poorly sited development projects have become more common (GRIGGS et al. 2005). Coastal management decisions are often influenced by the size of a development proposal or frequently made during imminent threat of storm-induced erosion. Management of our coastlines often has become piecemeal with permitting typically addressed on a parcel-by-parcel, case-by case basis. This has resulted in disruptions to sand transport, and a lack of consideration of cumulative impacts of development on beaches. There has been a recent recognition that we need a regional approach to balance the uses and pressures on our sand supply and beaches.

In watershed planning, significant work has been done on sediment budgets in fluvial systems, and on the impacts of humans on the delivery of sand and impacts associated with sand reductions (MEADE 1982, KONDOLF 1997, WILLIS and GRIGGS 2003, OWENS 2005, RENWICK et al. 2005, MAGOON and LENT 2005). Recent research and management efforts in littoral cell planning in Oregon and Washington (MARRA 1995, KAMINSKY et al. 1997, REVELL 2000), and regional sediment management (BEST and GRIGGS 1991, ROSATI et al. 2001, CSMW 2006) demonstrate a shifting scientific and management focus from a project/site specific approach to one encompassing the range of coastal processes across a variety of jurisdictions. The sandshed concept builds on coastal processes science and concepts of littoral cell sediment budgets or beach compartments (BOWEN and INMAN 1966, BEST and GRIGGS 1991, KOMAR 1996, KAMINSKY et al. 1997, HARNEY and FLETCHER 2004, PATSCH and GRIGGS 2006).

Building on these regional approaches, this paper describes the concept of a sandshed and the corresponding sandshed management framework as a holistic approach to managing sand in a way that preserves the recreational, cultural, ecological, and economic values of a beach as well as maintaining or improving inundation and erosion hazard protection.

SANDSHED MANAGEMENT

A sandshed can be defined as the area and processes that create an individual beach system - a watershed and a littoral cell framed within the context of geologic time and influenced by physical processes and human activities at decadal to century time scales. Each sandshed is unique, a river of sand from coastal mountains tops to the deep ocean floor. Each sandshed has its own physical and community characteristics whose interactions determine the economic, recreational, and ecological health of the beach.

Sandshed planning merges coastal engineering and planning with developing concepts of ecosystem and community based management. A sandshed supports the communities and ecosystems that depend on its functioning. Ecosystem-based management focuses on the interactions between all species and their natural environment. This has evolved from a single species emphasis to a more holistic approach. Maximum benefits in ecosystem-based management are achieved by maintaining linkages, a critical priority for sandshed management.

Sandshed management is a regional "beach-centric" approach to sediment management that focuses on maintaining sand supply to minimize hazards and maximize economic, ecological, and recreational opportunities. Sandshed management evaluates the factors affecting shoreline stability and assesses various hazard avoidance and mitigation strategies.

Critical steps to successful sandshed management include: inventory, analyses of risk and alternatives, and implementation (Figure 1). The inventory identifies unique physical and cultural characteristics of each sandshed and the mechanisms that affect shoreline stability. The analysis stage evaluates risk associated with the variety of hazards and the range of alternatives, from avoidance to mitigation with an emphasis on alternatives that preserve the beach and restore the sandshed. Implementation mechanisms can be matched with community needs to protect life, property, economic viability, and sandshed linkages.

INVENTORY

The inventory is a collection of information describing the cultural and physical characteristics of each sandshed. The cultural inventory focuses on jurisdictional factors, management questions, assets, community values, and human alterations across the sandshed. The physical inventory should identify the regional geographic setting, and the processes affecting shoreline stability with the sediment budget a key consideration. These inventories can be in map, database or text format, but form the basis for decision-making and hazard assessment. Ideally, this inventory should be created in a geographic information system (GIS), a computer software tool that integrates diverse maps and spatial relationships with databases and tabular information across a variety of spatial scales. The critical scale to streamlining management decisions is the parcel scale (~1:6,000), the scale at which most projects, permits, and decisions are made (REVELL 2000).

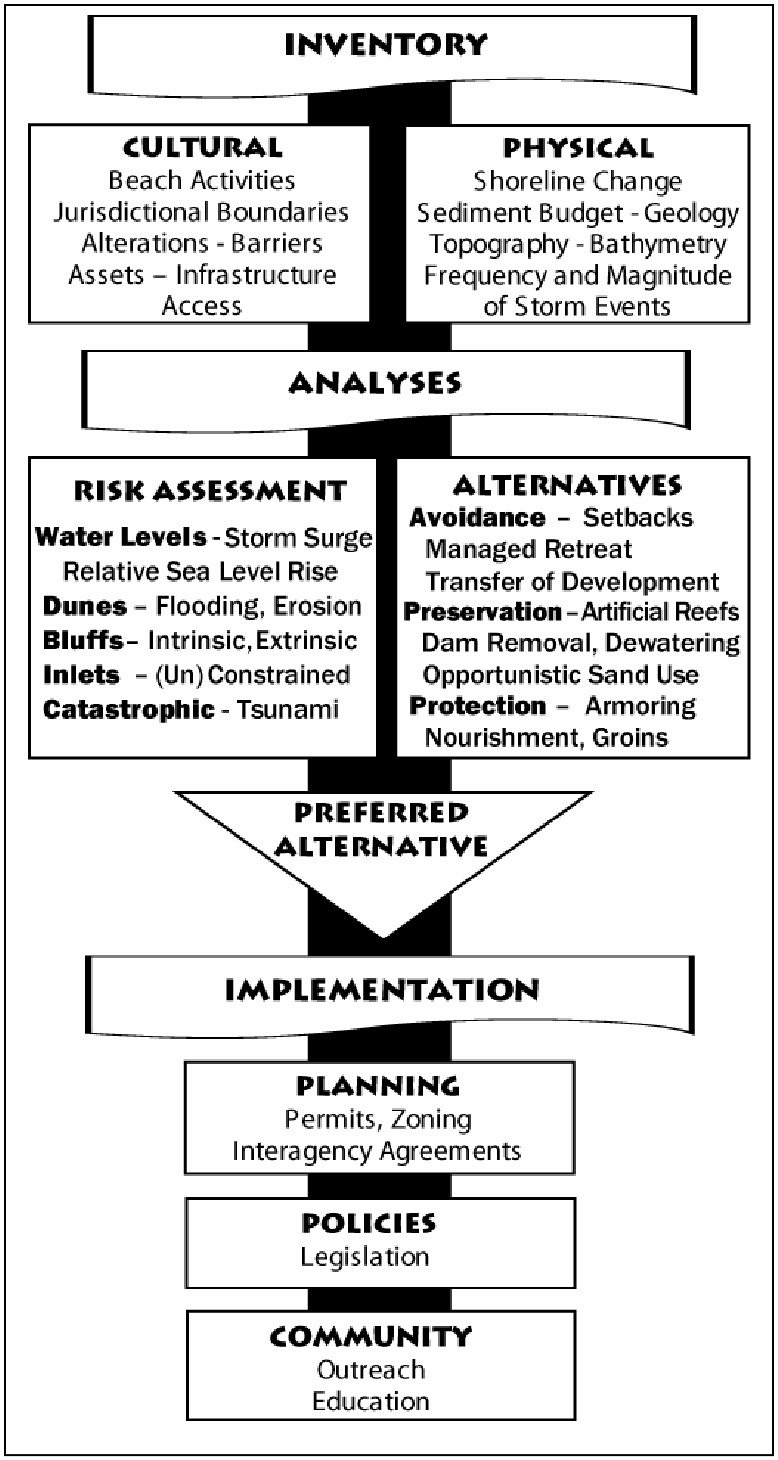

Figure 1. Sandshed Management– inventory, risk assessment and alternatives analyses, and implementation

Cultural Inventory

Components of the cultural inventory facilitate management decisions and planning by combining planning level information with community priorities, infrastructure, and environmental and cultural assets (Figure 1).

Cultural inventory data sets should include locations of critical facilities such as hospitals, and emergency service providers. Infrastructure such as ports and harbors, and bridges should be cataloged as well as locations of watershed alterations including culverts, dams, contaminated sediments and debris basins. Jurisdictional boundary information facilitate planning and implementation by identifying zoning, urban growth boundaries, and property boundaries. The cultural asset inventory should be attributed with information relating to structural footprints, shoreline armoring, and assessment values. Community priorities include information on beach activities, recreational use patterns, public perceptions and beach access. Finally, environmental assets should be inventoried to identify unique habitats and threatened and endangered species.

Humans change our coasts daily with the scales of alterations ranging from sand castles to shore protection structures (WEIGEL 2002, GRIGGS 2005) to global sea level rise (IPCC 2001). Many human alterations have long-term impacts to our beaches. Understanding the differences between “natural” sand supply and “actual” supply can provide critical information on cumulative impacts (WILLIS and GRIGGS 2003, RUNYAN and GRIGGS 2003). The most disruptive alterations to sand supply are dam and debris basins (SHERMAN et al. 2002, RENWICK et al. 2005), sand mining (MAGOON and LENT 2005), coastal armoring, and jetties and breakwaters associated with ports and harbors.

Visioning and needs assessments provide cultural information on community values and priorities. Is the community heavily dependent on its harbor? What role do beaches play in providing recreational opportunities, and what are the types of recreational uses? Is the shoreline urbanized, rural, or natural? Who and how many people are using the beaches? These answers provide valuable information for assessing hazard avoidance and mitigation alternatives.

Physical Inventory

The purpose of the physical inventory is to distinguish the geographic setting and understand the factors that affect shoreline stability at different time scales. These factors can be broken down into small chronic events that occur over years to decadal scales and catastrophic events that occur in hours to days.

The regional setting should identify the general climate and tectonics including major geographic features, watershed basins, headlands, submarine canyons, rivers, estuaries and offshore reefs. Climate controls also play a significant role in shoreline stability, and should be included in the inventory stage. Sea level, wave variability, and sediment discharge have been related to climatic events such as El Niño, the North Atlantic Oscillation, and the Pacific Decadal Oscillation. (INMAN and JENKINS 1999, ROONEY and FLETCHER 2005, ALLAN and KOMAR 2006, PAPADOPOLOUS and TSIMPLIS 2006). Regional shoreline responses to climatic events have been observed in the form of beach rotations (SALLENGER et al. 2002, REVELL et al. 2002, RANASINGHE et al. 2004), and related to changes in wave direction (GRAHAM 2003, BROMIRSKI et al. 2003, ROONEY and FLETCHER 2005).

Chronic changes are largely controlled by the sediment budget, which is a balance between the sources, storage and sinks of sand within a sandshed (BOWEN and INMAN 1966, BEST and GRIGGS 1991, KOMAR 1996, and ROSATI 2005). The more quantified the budget, the better the potential to assess cumulative impacts of alterations in the sandshed to the community and beaches.

Natural sources of sand include river and stream discharge and dune and bluff erosion. Littoral cell cut-off diameter is the minimum sand grain size found on the beaches and is a new but very important consideration. This grain size is important for assessing the volumes of beach compatible sand from bluff erosion and river discharge (BEST and GRIGGS 1991, LIMBER et al. in press). It is related to beach and offshore slopes, incident wave energy, and geology. Littoral drift rates are a function of wave energy and direction, as well as sand supply, and should be assessed to determine sand transport directions.

Rivers and streams contribute most of the beach sands to the U.S. West Coast. Sand volumes can be estimated using sediment-rating curves, in which measured values of water discharge show the relationship between water volumes discharged and sediment loads. Fluvial sand discharge is episodic, occurring primarily during the highest flow and precipitation events (WILLIS and GRIGGS 2003, INMAN and JENKINS 1999). Dune and bluff erosion depends on water levels, wave attack, vegetation, and composition (SHIH and KOMAR 1994, MOON and HEALY 1994, WILCOCK et al. 1998, BENUMOF and GRIGGS 1999, RUGGIERO et al. 2001). The inventory should identify backshore composition, and collect data on historic wave and water levels.

The primary sink of sand in most littoral cells is offshore, whether deposited on the shelf during large storm events or transported down submarine canyons (KOMAR 1996, ROSATI 2005). Dunes can also be an important sink as sand is blown into dunes and removed from the beaches (BOWEN and INMAN 1966, KOMAR 1996).

Long-term shoreline change trends have been assessed using a variety of techniques (MOORE 2000, BOAK and TURNER 2005 for recent reviews). Regional shoreline assessments have been completed by the USGS for the Gulf Coast, Southeast Atlantic

Coast, and California Coast (MORTON et al. 2005, MORTON and MILLER 2005, HAPKE et al. 2006). Long-term rates provide valuable information on shoreline trends that directly affect future hazards and are often indicative of beach sand supply.

Sea level changes associated with storm surges and El Niños increase hazards to those living in vulnerable areas. Eustatic or global sea level rise and relative or local sea level rise are critical to inventory because of the potential to increase hazards by exposing coastlines to higher water levels more frequently (KOMAR 1998, GRIGGS et al. 2005).

Historically, beach profiles have provided information on seasonal changes to beaches and the response of the shoreline to episodic storm events. The recent application of detailed topographic LIDAR to regional assessments and large-scale coastal behavior has provided opportunities to quantify regional changes from individual storm events (SALLENGER et al. 2002, REVELL et al. 2002, SALLENGER et al. 2005.)

Catastrophic events leave a profound imprint on the shoreline. Major hurricanes, subsidence events, and tsunamis accelerate existing erosion problems and often displace entire communities. Inundation lines and elevations are important to quantifying catastrophic hazards. While these disasters are unpredictable, the inventory should assess the frequency and magnitude of historic events.

ANALYSES

Risk Assessment

The purpose of the risk assessment is to identify what areas are most susceptible to various hazards and what assets are at risk. The information gathered in the inventory stage is used to assess risk at the parcel scale as well as cumulatively in the sandshed. The risk assessment should be based on failure mechanisms, magnitudes, and probabilities of recurrence along each backshore type. Including the trends of shoreline change and role of beaches in the assessment improves the ability to identify hazardous areas (CROWELL and LEATHERMAN eds. 1999, HEINZ CENTER 2000, RUGGIERO et al. 2001, SALLENGER et al. 2002).

To accurately identify the risk associated with construction on dunes, bluffs, and inlets, it is important to apply the appropriate local parameters on existing conditions, the planning horizon, rates of shoreline change, expected increases due to sea level rise, and extreme storm event probabilities. Various models and methods have been developed to identify hazardous areas during a variety of potential erosion events (CROWELL and LEATHERMAN eds. 1999). While an in-depth discussion of potential models is beyond the scope of the paper, it is important to use caution when applying erosion models and dealing with uncertainties (THIELER et al. 2000, CROWELL et al. 2006).

With dunes, the hazards arise from overtopping and inundation as well as erosion and undercutting. The flooding and overtopping hazards can be mapped using a total water level model comprised of sea levels and wave run-up components (RUGGIERO et al. 2001) combined with detailed topographic information. The magnitude of coastal dune erosion can be approximated using a geometric model approach based on equilibrium profiles (KOMAR et al. 1999). The use of scientifically "accepted" scenarios of extreme wave statistics, wave run-up, and sea level rise, can identify the range of risks which can then be applied based on the amount of risk acceptable to a community.

With bluffs, the failure mechanism is largely determined by intrinsic factors, the structure and composition of the bluff material (MOON and HEALY 1994, BENUMOF and GRIGGS 1999). In bluffs undergoing gradual retreat, extrinsic factors such as the hours of wave attack at the toe of the bluff at high tide and the width of the beach (WILCOCK et al. 1998, RUGGIERO et al. 2001, SALLENGER et al. 2002, as well as the strength of the materials (MARRA 1995, RAHN 1996) should be incorporated in risk assessment. In bluff-backed areas susceptible to episodic events, such as block slides and landslides, the size of the failure should be measured with the probability of reactivation incorporated into identifying relative risk zones (RAHN 1996, PRIEST 1999 in CROWELL and LEATHERMAN eds. 1999).

Inlets, can be separated into constrained, typically controlled by jetties or breakwaters; or unconstrained, face flooding and sedimentation during high wave and precipitation events. Storm discharge in constrained inlets can lead to navigational hazards, while unconstrained inlets are subject to inlet migration or breaching of new inlets. Assessing the tidal prism volumes provides information on sedimentation rates and flushing capacity. Changes to the tidal prism over time reflect changing conditions in the sandshed. Unconstrained inlets can be assessed using historic inlet locations and trends in migration. Constrained inlets generally involve ports and harbors with hazards associated with dredging and contaminated sediments (APITZ and POWER 2002).

Regional hazard assessments should couple process-based models tuned to local conditions to classify the relative risk along the coastline at an individual parcel scale. Delineating high to low risk hazard zones, for example, can be used as setbacks for new development. Hazard assessment methodologies need to be transparent to the community with significant input from coastal process scientists and engineers.

Alternatives Analysis

Assessing risk and identifying the range of alternatives and then filtering them with cost/benefit, cumulative impact, and community values can lead to the identification of a preferred alternative and facilitate implementation at the appropriate scale (Table 1). There are three categories of alternatives, those that– avoid hazards, preserve the beach, or protect the shoreline.

There are many mechanisms to reduce future hazards along developing and rural coastlines. Along undeveloped coastlines, hazard avoidance can be achieved by siting development away from hazardous areas, or by acquiring identified vulnerable areas. Along developed coastlines there are additional challenges, but by creating a sandshed plan, redevelopment and new development can be sited to minimize hazards and cumulative impacts and preserve the beach. Based on relative sea level rise rates for a community, managed retreat may be the most cost effective approach over the long term. Ideally, sandshed plans will be utilized during post-disaster recovery to remove damaged infrastructure and properties from hazardous areas and retrofit linkages within the sandshed.

An important focus of sandshed management is to restore and maintain sand transport, supply and sandshed linkages. In developed sandsheds, opportunities can be seized to increase sand supply by expanding culverts, widening bridges, removing dams and debris basins and better siting of infrastructure. In places of high alterations and poor linkages, altering port configurations or developing opportunistic beach nourishment programs (CSMW 2006) can artificially maintain linkages and sand supply.

Shoreline armoring has been shown to have a variety of effects on the shoreline (WEIGEL 2002, GRIGGS 2005, DUGAN and HUBBARD 2006). Individual structures may cut off refuges to species during storm events, or prohibit beach access during certain tides levels. Nourishment may change beach characteristics reducing reproductive success for sea turtles, or forage fish like grunion and surf smelt, primary food for salmon which breed up the sandshed on the sands and gravels. Using a sandshed approach examines alternatives that preserve the beach and assess the cumulative impacts of coastal development. Cumulative impacts to the sediment budget can be quantified in the context of "natural versus actual" sand supply. Other cumulative impacts can be assessed based on impacts to character of the beach, community identity, and specific impacts to recreation, and beach ecology.

Incorporation of community beach values often encourages habitat restoration, open space protection, and alternative shore protection structures that enhance or mimic natural processes to increase sand retention and promote recreation using artificial surf reefs, beach dewatering, geotextiles, and sand/cobble nourishment.

External costs such as the loss of beach access, quality of recreational experience, or reduced risk need to be included when weighing more traditional cost/benefit analyses.

Localized management measures provide opportunities to couple data collection with community needs. Beach-grooming tractors, or lifeguard vehicles can conduct repeat topographic surveys of beaches. This can enhance opportunities to leverage limited funds and achieve the goals of sandshed planning.

Sandshed education can be incorporated into primary and secondary curriculum linking the land and the sea leading to an expanded community support for beach restoration, resource protection, and coastal management. The end result will be an educated citizenry that supports beach health and hazard avoidance over hazard mitigation.

IMPLEMENTATION

There are a number of different agency actions or agreements that can be taken to ensure that policies and strategies that constitute the sandshed plan are applied consistently by all levels of government. Relevant portions of the sandshed plan can be implemented through memoranda of understanding, or coordination agreements. Plans and timelines for monitoring, maintenance, and revision should be included in these agreements. Nationally, hazard insurance rates and tax incentive programs can be revised to prioritize hazard avoidance over mitigation with recurring problem areas targeted for acquisition or relocation.

Scale	Avoidance	Preservation	Shore Protection
Global	Development Guidelines Education, Relocation	Acquisition, Restoration	Port and Harbor Construction
National	Acquisition, Hazard Insurance, Incentives	Nourishment, Dam Removal	Ports and Harbors, Breakwaters
Sandshed	Managed Retreat, Transfer Development Rights	Retrofit Linkages Sand Bypassing, Dam Removal Opportunistic Beach Fill	Ports and Harbors, Shoreline Armoring
Community	Planning, Inventory Adoption, Geologic Reports	Debris Basin Cleanouts, Setbacks, Sand Backpassing	Groins, Shoreline Armoring
Beach	Opportunistic Beach Fill	Artificial Surf Reefs, Beach Dewatering, Geotextiles	Groins, Shoreline Armoring
Parcel	Setbacks, Managed Retreat	Erosion/Drainage Control	Seawalls, Revetments

Table 1: Sandshed implementation mechanisms by scale.

At the sandshed scale, local governments can formally adopt hazard zone and inventories through comprehensive plan updates and zoning ordinances. Following inventory adoption and agreements, management mechanisms become more localized. In day-to-day activities, management decisions regarding building permits and sandshed alterations should consider both identified hazards and cumulative impacts. Specific implementation mechanisms could apply hazard zone maps to delineate insurance rates, establish setbacks or trigger geologic reports with specific requirements pertaining to slope, run-off or vegetation management.

CONCLUSION

Beaches provide economic benefits, recreational opportunities, wildlife habitats, storm protection, and inspiration. Beaches are trapped between sea level rise on one side and the increasing migration of people to coastal areas on the other. Many of the concepts presented in this paper are not new, but the incorporation of the complexities of watershed planning, sediment budgets, regional sediment management, and littoral cell planning into a holistic "sandshed" concept can reinvigorate community involvement and aid decision making in matters affecting beach and community health. A sandshed approach blends science with management in a way that maintains inundation and erosion protection potential and recreational and ecological resource value. By including community values into hazard avoidance and mitigation strategies facilitates an understanding of linkages along sand pathways. Collectively these sandshed concepts can build an educated constituency that values the sand on our beaches and will vote, activate, and educate to protect our endangered beaches.

There are many benefits of sandshed management. Hazard assessment is more consistent when carried out on an area wide basis. Hazard avoidance is more feasible when considered prior to development. Hazard mitigation is more cost effective when addressed at the same scale as factors affecting shoreline stability. Through the compilation of a sandshed inventory and hazard assessment, we can better assess cumulative impacts to our beaches. This management scheme can facilitate post-disaster reconstruction by identifying opportunities to retrofit sandsheds and avoid hazards. Sandshed management enhances interagency cooperation and provides opportunities to communicate and educate other sectors of the community with the additional benefits of streamlining permitting and decision-making.

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