INFLUENCE OF HARBOR CONSTRUCTION ON DOWNCOAST MORPHOLOGICAL EVOLUTION: SANTA BARBARA, CALIFORNIA

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Abstract: Sand impoundment caused by construction of the Santa Barbara Harbor in the 1920s, created an erosion wave that impacted downcoast Carpinteria Beach. Historic beach and shoreline changes were analyzed to understand continuing erosion using a combination of historic air photos, lidar, and physical measurements. The long-term analyses show a clockwise rotation with erosion of -0.35 m/yr at the updrift end and accretion downdrift of 0.3 m/yr. Storm impacts measured before and after the 1982-83 and 1997-98 El Niño events show similar rotation patterns, providing evidence that El Niños may be driving coastal evolution. Differences in shoreline responses between El Niño events show that the erosion hotspot migrated downdrift following construction of a revetment after the 1982-83 storms. Seasonal field measurements in the winter show beach narrowing while sediment coarsen variably alongshore. The coarsest materials and erosion hotspot are co-located at the end of the revetment on the city beach.

INTRODUCTION

Carpinteria, California, is a 1.5 km sandy beach 15 km downdrift of the Santa Barbara harbor in the middle of the Santa Barbara Sandshed. 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, to the Point Mugu submarine canyon in the south (Figure 1). Point Conception and the Channel Islands to the south create a narrow swell

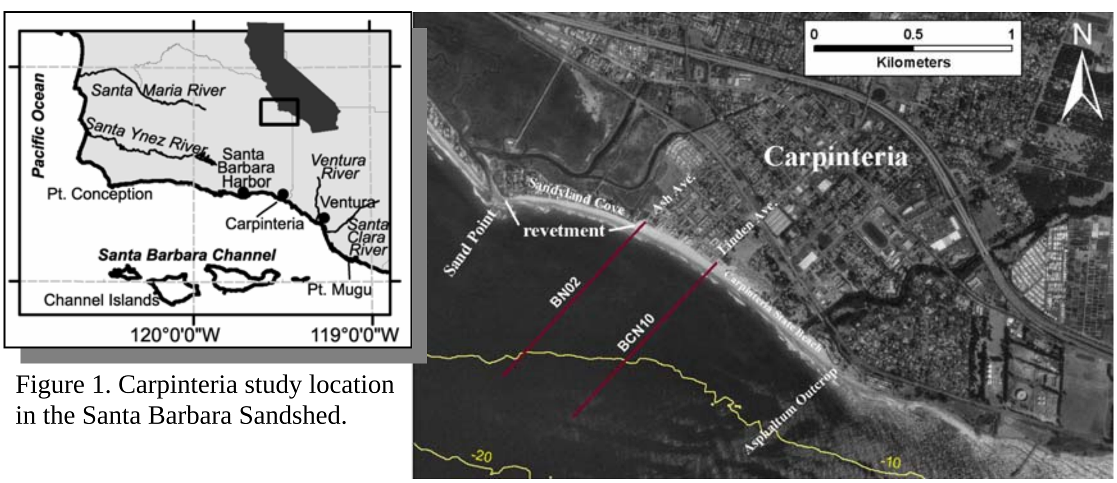

Figure 1. Carpinteria study location in the Santa Barbara Sandshed.

window to open ocean waves that shelter much of the south facing coast of Santa Barbara County from extreme wave events (Figure 1). Breakwater construction at the Santa Barbara Harbor began in 1927 and was completed by 1930, during which ~ 2 million cubic meters of sand were impounded updrift of the Santa Barbara Harbor. Sand impoundment led to a well documented erosion wave that migrated downcoast at ~1.7 km/yr leading to the erosion of the historic dune field at Sandyland and the beach at Carpinteria in the late 1930s (e.g. Bailard, 1982; Komar 1998; Weigel 2002 and references within) (Figure 2).

Carpinteria Beach can be broken into three parts based on jurisdictional boundaries. At the west end is Sandyland Cove, the central portion is the city of Carpinteria, and at the east end is the Carpinteria State Beach (Figure 1). The Carpinteria study examined changes the updrift Sand Point in the west to an Asphaltum outcrop downdrift in the east.

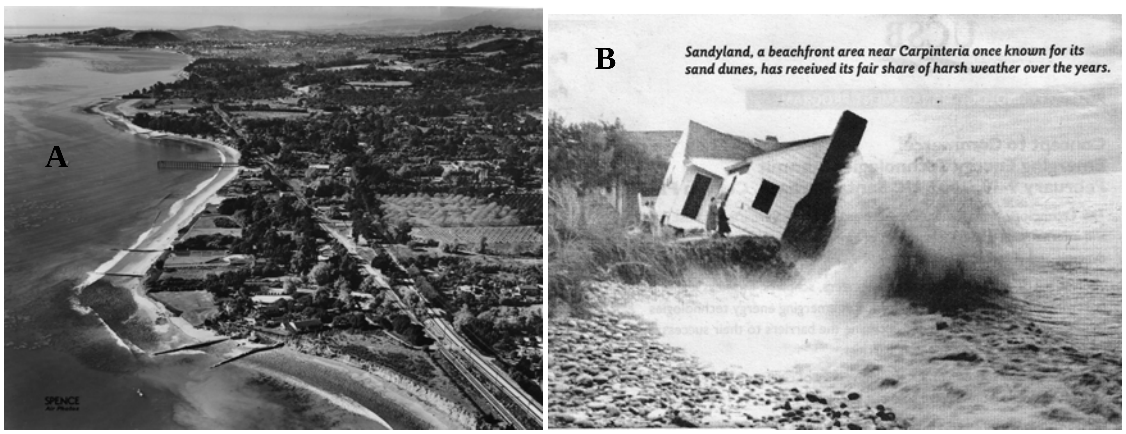

Figure 2. Historic Photos a.) 1936 image with erosion wave en route to Carpinteria (photo Spence Collection – UCLA), b.) updrift Sandyland circa late 1930s (photo Santa Barbara Independent).

While the reporting of this erosion wave and its impacts is not new, the application of modern photogrammetric, GIS, and state-of-the-art geologic field techniques to examine the manmade disaster provides insights into ongoing erosion hotspots and coastal evolution at a variety of temporal scales from long-term (1869- present) to seasonal.

METHODOLOGY

The historic shoreline and beach width changes were documented using a combination of historic beach profiles, topographic maps, aerial photography, lidar and Global Positioning System (GPS) survey techniques. Historic beach profiles were collected quasi-periodically every 5 years with irregular seasonal sampling from 1987 to 2005. Profile analyses examined changes in beach slopes, shoreline position, and beach volumes relative to a 1987 baseline at Mean Sea Level (MSL, +83cm) and Mean Lower Low Water (MLLW, -27cm) North America Vertical Datum 1988 (NAVD88). Only the results from the subaerial (dry sand) portion of the profile are reported in this paper.

For this study, 12 different sets of rectified vertical summer/fall air photos were obtained for the period from 1929 to 2003. The use of historic National Ocean Service (formerly US Coast and Geodetic Survey) topographic sheets in 1869 and 1933 extend the duration of the shoreline change analyses to 138 years. Tide level corrections were applied to the wet/dry proxy shorelines and the historic T-sheets High Water Line (HWL) shoreline to adjust the wet/dry shorelines to MSL using historic hourly water level data at Santa Barbara harbor (Station #9411340, National Oceanic and Atmospheric Administration, 2007). Due to the typical low energy waves found in the Santa Barbara Channel during the summer and fall, wave run-up adjustments were not included in the proxy-based shoreline correction (Ruggiero *et al.* 2003; Moore *et al.*, 2006). More details on methodologies and uncertainties can be found in Barnard (in press).

Two shoreline reference features were digitized from each image- the wet/dry line and the back beach, with the distance between these two features defined as the beach width, generally the dry subaerial portion of the beach. Shoreline change and beach widths were calculated along the same 50-meter spaced transects drawn from an offshore baseline using the USGS Digital Shoreline Analysis System (DSAS, Thieler *et al.* 2005). This study reports on the shoreline change linear regressions rates (LRR). Using the intersection locations of the shorelines along each transect, shoreline positions relative to the 1869 baseline were calculated. Sand volumes per transect (m^3/m) above MSL were calculated and transect volumes were multiplied by the 50 m transect spacing and summed alongshore to provide a total shoreline volume.

Applications of high accuracy, topographic Lidar and GPS data provides information on regional beach volumes and shoreline changes caused by extreme storm events such as the 1997-98 El Niño event (Sallenger *et al.* 1999; Revell *et al.* 2002; Sallenger *et al.* 2003). An additional lidar data set collected in October, 2005 by the University of Texas and has been included in these analyses. Between 2005 and 2007, topographic data were collected seasonally using Differential GPS mounted on all terrain vehicles (ATVs) to survey the sub-aerial beach (Barnard *et al.* in press).

Topographic data sets were clipped to the study area and grids created at 2 m resolution using standard inverse distance weighting methods in ArcGIS to identify storm and calm seasonal changes, shoreline position and beach volume changes. These grids were 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. Both reference features were included in the beach width analyses, with the 1997 and 2005 MSL shoreline included in the shoreline change analyses.

Seasonal sediment samples from the beach face were collected with the ‘Beachball’ camera, a 5-megapixel digital camera encased in a waterproof housing (Rubin 2006) and validated by Barnard *et al.* (2007). To evaluate the spatial variability of the various grain sizes on the subaerial beach, all grain size samples were interpolated using a Triangular Irregular Network (TIN) and then gridded at 5 m using the standard inverse distance weighting function in ArcGIS.

Since Carpinteria is downdrift of the Santa Barbara Harbor, we expected a correlation between the volume of sand dredged at the harbor and the volume of sand found on Carpinteria Beach. A lagged cross-correlation analysis was conducted between the harbor dredge records (Patsch and Griggs 2007) and a smoothed summer/fall beach volume data set for the entire Carpinteria coastline. For more details on this procedure please see USGS Open File Report on the Carpinteria Coastal Processes (Barnard *et al.* in press).

RESULTS

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, respectively, with more recent photography having lower spatial errors on the order of +/- 7m based on a quadrature, or sum of the squares method (Hapke *et al.* 2006, Barnard *et al.* in press).

Historic Profile Analyses

Profile analysis reveals differences between the response at the MSL and MLLW portions of the beach (Figure 3, Barnard *et al.* in press). The MSL shoreline position has been relatively stable, retreating <1 m over the interceding 18 years, while the MLLW shoreline position migrated seaward by ~15 m, indicating a decrease in beach slope or a

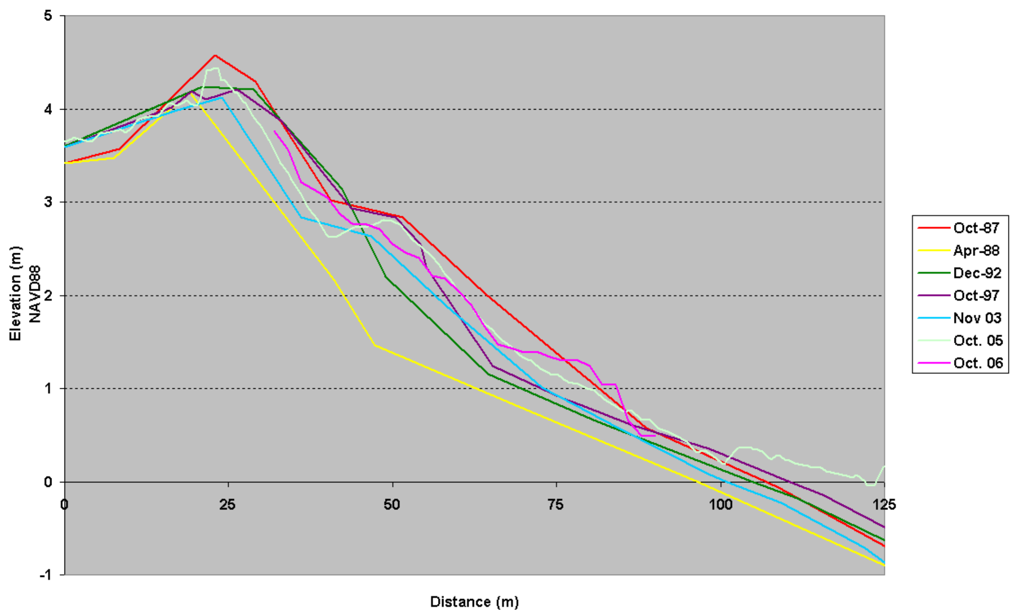

Figure 3. Historic profiles taken at BEACON 10. See Figure 1 for profile location

flattening of the beach profile over time. In general, a relationship typically exists between shoreline changes and volume changes causing the shoreline to retreat (accrete) as sand volume is lost (gained) (e.g. Farris and List 2007). This pattern generally fits although the relation between the MLLW shoreline position and sand volumes, showing wider variability than MSL and poorer relation between volume and shoreline position. In light of the high variability of the MLLW portion, further analyses focused on the MSL shoreline as a more stable shoreline indicator.

Historic Volume Changes

Time series from 1929-2006 of summer/fall subaerial beach sand volumes above MSL for the Carpinteria coastline are shown in Figure 4. The maximum beach volume along this coastline occurred in 1929 and is estimated to be ~400,000 m^3. Although the Santa

Barbara Harbor was impounding sand by 1929, measurements from the 1929 photo at Carpinteria represent pre-harbor conditions, as Carpinteria Beach had not yet been impacted by the erosion wave. The largest reduction in beach volume (~175,000 m^3) occurred between 1929 and 1938 as the erosion wave migrated through Carpinteria. Since 1929, the total volume of sand at Carpinteria has never recovered to pre-Harbor conditions (Figure 4). The minimum beach volumes (~93,000 m^3) measured during the study occurred in 1989 several years after the 1982-83 El Niño event. The late 1960s and 1970s had the highest beach volumes. There has been a long-term decrease in beach

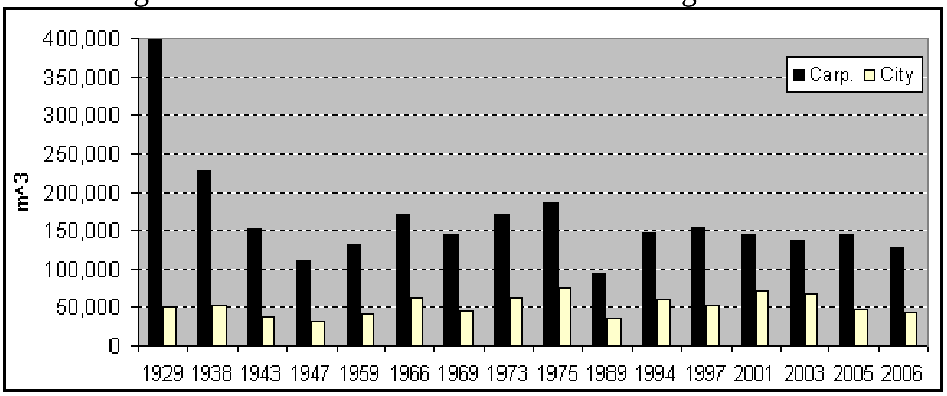

Figure 4. Total beach volumes (above MSL) from 1929-2007, 1929-1994, 2001, and 2003 from aerial photography; 1997, 1998, and 2005 from lidar; 2006 from GPS surveys.

volume across Carpinteria. The City of Carpinteria Beach shows a slightly different trend in beach volumes. Through the historical record, the City of Carpinteria Beach has contributed a higher percentage of sand to the overall sand volumes found along Carpinteria. Since 1959, the beach fronting the City of Carpinteria had 30% to 50% of the total subaerial sand volume found along this entire stretch of coastline.

Historic Beach and Shoreline Changes

Historically, beach widths along Carpinteria have oscillated, ranging from zero to 80 m, with mean summer/fall beach widths ranging from 20 to 60 m. Minimum and maximum beach widths found at each transect do not fit any temporal pattern; there is no clear relationship between beach width, El Niño events and/or erosion wave. Beach changes from 1929 to 1938 following the erosion wave are shown in Figure 5. While beach

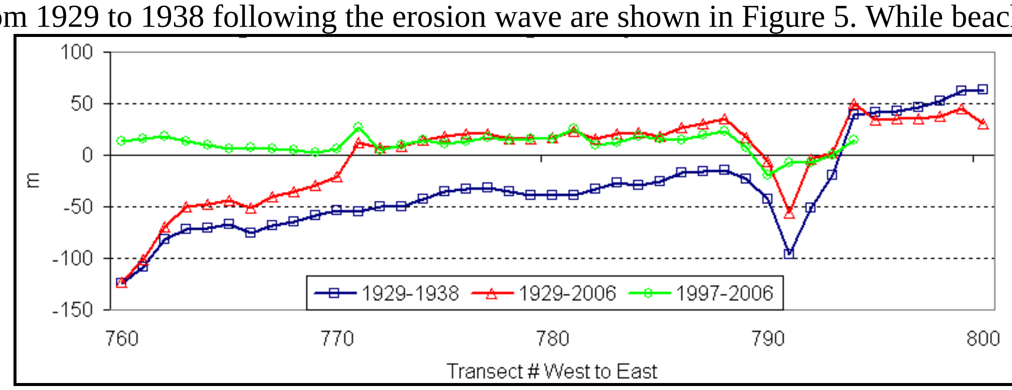

Figure 5. Beach width changes from 1929 baseline. Shown are the long-term changes from 1929 to 2006, the changes immediately following the arrival of the erosion wave between 1929 and1938, and the recent changes from 1997 to 2006. Note that Carpinteria Creek outlets between transects 791-793.

widths were decreasing in the west (~125 m), there was also widening of the beach at the east end of the shoreline segment (~50 m). The beach has maintained this alignment for the subsequent 67 years (1938-2006), although the center of the beach widened ~10 m and the beach width changes since 1997 including the intense 1997-98 El Niño event had no long-term impacts (Figure 5). Without shore protection structures, the beach width should remain relatively constant, migrating inland or seaward depending on the amount of sand in the system (Komar 1998). This pattern was examined by investigating changes to both shoreline features.

The shoreline change analysis shows a similar pattern of updrift erosion and downdrift accretion (Figure 6). Changes in actual shoreline location in 1929 and in 2006 (Figure 7)

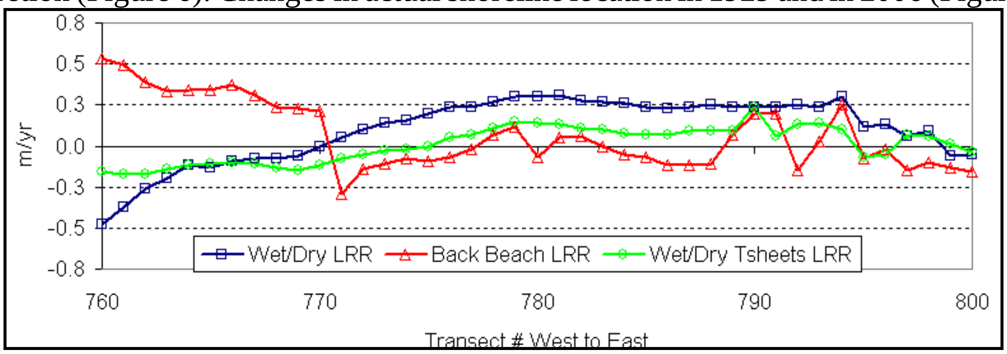

Figure 6. Shoreline change linear regression rates of the various shoreline reference features.

also show this pattern of updrift erosion and downdrift accretion. However, the back beach change rate shown in Figure 6 at the west end (transects 760-770) shows an accretion trend related to the placement loss of the revetment advancing the back beach seaward. The back beach shoreline changes adjacent to the revetment (transects 770-780)

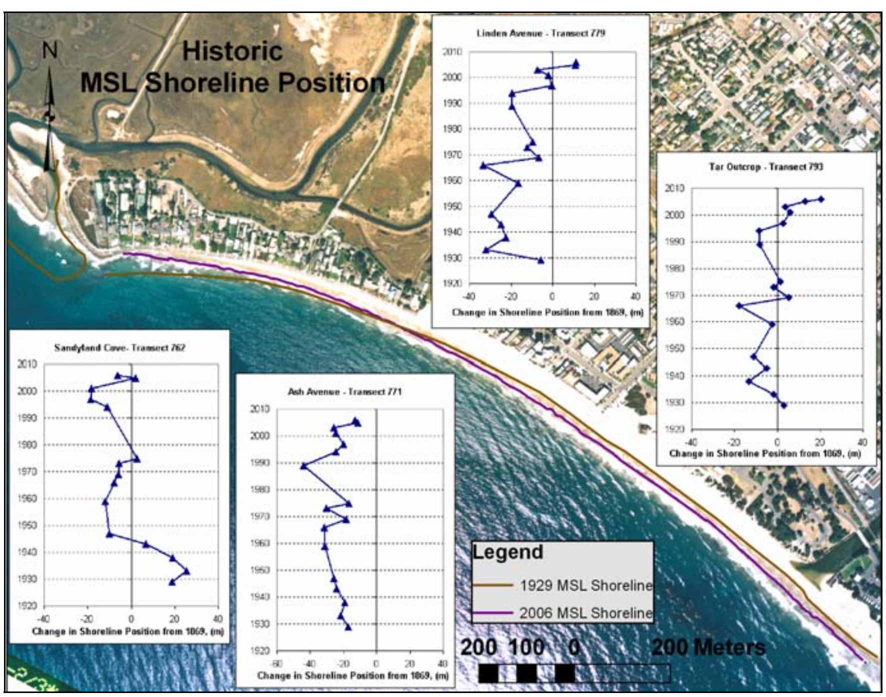

Figure 7. Changes in MSL shoreline position relative to the 1869 shoreline at four locations. The 1929 and 2006 MSL shorelines also show updrift erosion and downdrift accretion

parallels the wet/dry shoreline pattern of erosion in the west and accretion in the east. To analyze the alongshore variability of the shoreline change data, shoreline positions were plotted for four locations along the Carpinteria coastline (Figure 7). The west end, now armored, has experienced a strong erosion trend following early accretion between 1869 and 1938. This accretion can be explained by the migration of a sandspit seen in 1869 at Sand Point onto the beach by 1929 (Barnard *et al.* in press). Part of the nearshore changes can also be seen in the bathymetric changes near Sand Point between 1933 and 1978 (Figure 8). Shoreline position at the Ash Avenue location has been regularly 20-30 m landward of the 1869 shoreline position, while the downdrift locations following erosion in the early 1900s experienced ~20 m accretion since 1869.

Nearshore bathymetric changes extracted from NOS surveys in 1933 and 1978 show a nearshore erosion hotspot near Sand Point (Figure 8). These changes are consistent with anecdotal evidence (Bailard 1982, and personal comm. 2007) of the deterioration of a sandspit and the erosion of a sand deposit that used to extend off of Sand Point prior to the passage of the erosion wave (Barnard *et al.* in press).

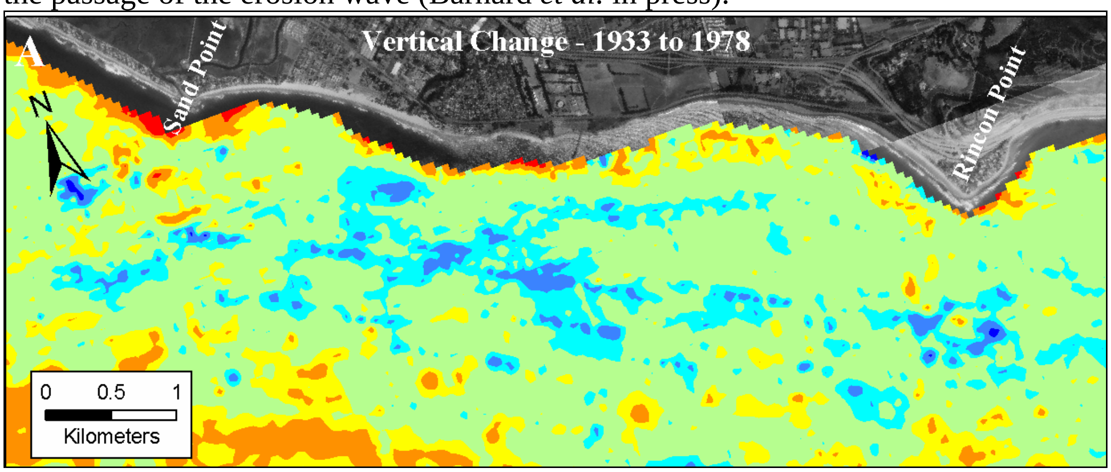

Figure 8**.** Bathymetric changes calculated from historical NOS surveys modified from Barnard in press.

Seasonal Beach Width and Shoreline Changes

Beach width changes extracted from the seasonal surveys in October, 2005 to February, 2007, are shown in Figure 9. Between October, 2005 and March, 2006, beach widths

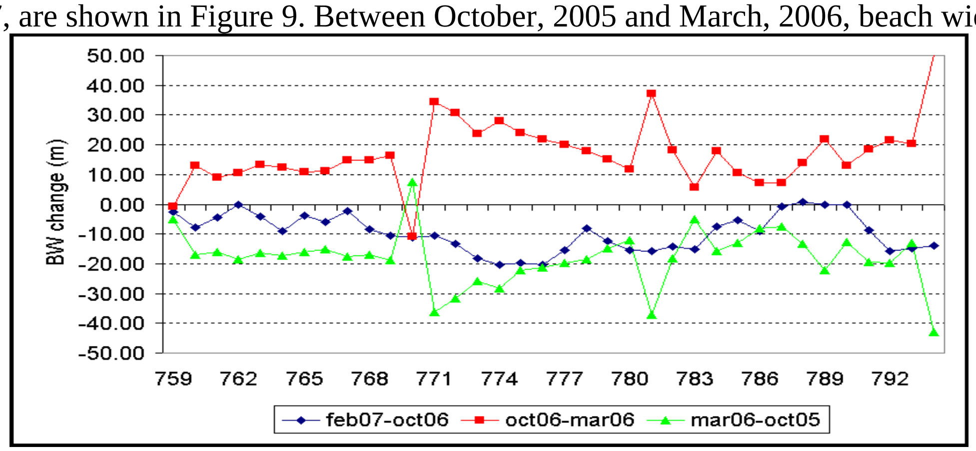

Figure 9**.** Seasonal beach width changes for the Carpinteria coastline. City Beach is located to transects 771-779. Shoreline armoring (revetment) occurs from transect 759 to 770.

narrowed by an average of ~ 20 m, with the greatest decreases downdrift of the Sandyland Cove structure. The peaks at transects 781 and 793 are found at a volleyball court and inlet to Carpinteria Creek, both features influencing back shore identification. Beach width changes between March and October 2006, show a summer beach recovery (Figure 9). Differences occur primarily in front of the revetment (transects 760-770) where recovery in October was slightly less than during the winter erosion. Seasonal changes between October, 2006, and February, 2007, are disguised in part by a winter berm constructed in front of the city of Carpinteria. It is apparent that the maximum erosion (Transect 771-774) occurs near the end of the revetment causing the beach to narrow ~20 m.

El Niño Response

El Niño events impact the entire US West Coast and have been shown to have significant impacts to beaches in the Santa Barbara littoral cell (Revell and Griggs 2006, Revell 2007). The lidar- and air photo-derived beach widths were combined to examine the response and recovery of the beaches to the large El Niño events of 1982-83 and 1997-98 (Figure 10). Beach changes reveal a rotational pattern of updrift beach erosion and

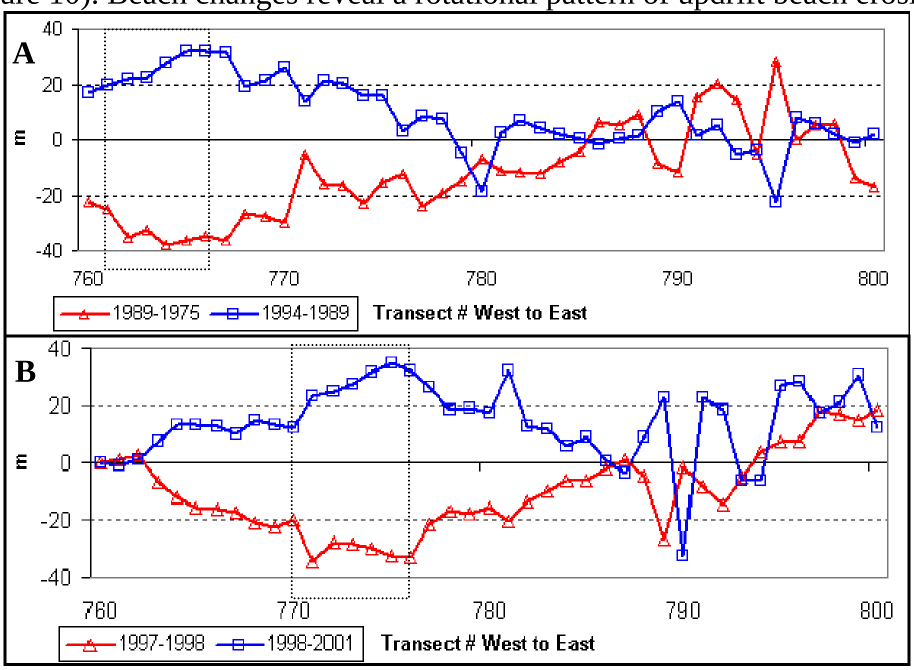

Figure 10. Beach width changes and recovery following the A) 1982-83 and B) 1997-98 El Niños. Erosion hotspots depicted in the boxes, and photo dates shown in legends.

downdrift accretion, characterized by nearly 40 m of narrowing at the west end and ~20 m of beach widening near the east end. By September 1994, the erosion hotspot had nearly recovered to pre-event beach widths. Following the 1982-83 El Niño event, a revetment was constructed from upcoast Sand Point to transect 770 to protect the oceanfront property. Examination of the lidar beach widths between 1997 and 1998, reveal similar rotation pattern and erosion magnitudes as the 1982-83 El Niño event. Between these two El Niño events the erosion hotspot shifted eastward ~ 500 m.

To examine the transport time of sand dredged from the harbor arriving at Carpinteria, a lagged cross correlation analyses on the smoothed Santa Barbara Harbor dredge record and a linearly interpolated summer/fall beach volume data was conducted (Barnard *et al* in press). The results of this analyses show that the maximum correlation coefficient (r^2 = 0.81) occurs at 4 years, significant at the 1% confidence level (n=14). The raw dredge data and the smoothed beach volumes also show a significant correlation with the peak lag also at 4 years (r^2 = 0.68), significant at the 1% level (n=14).

Beach Sediment Sampling

Mean grain size fluctuated seasonally between medium and fine sand, but locally could vary by up to a factor of two between summer and winter samples (Barnard *et al.* in

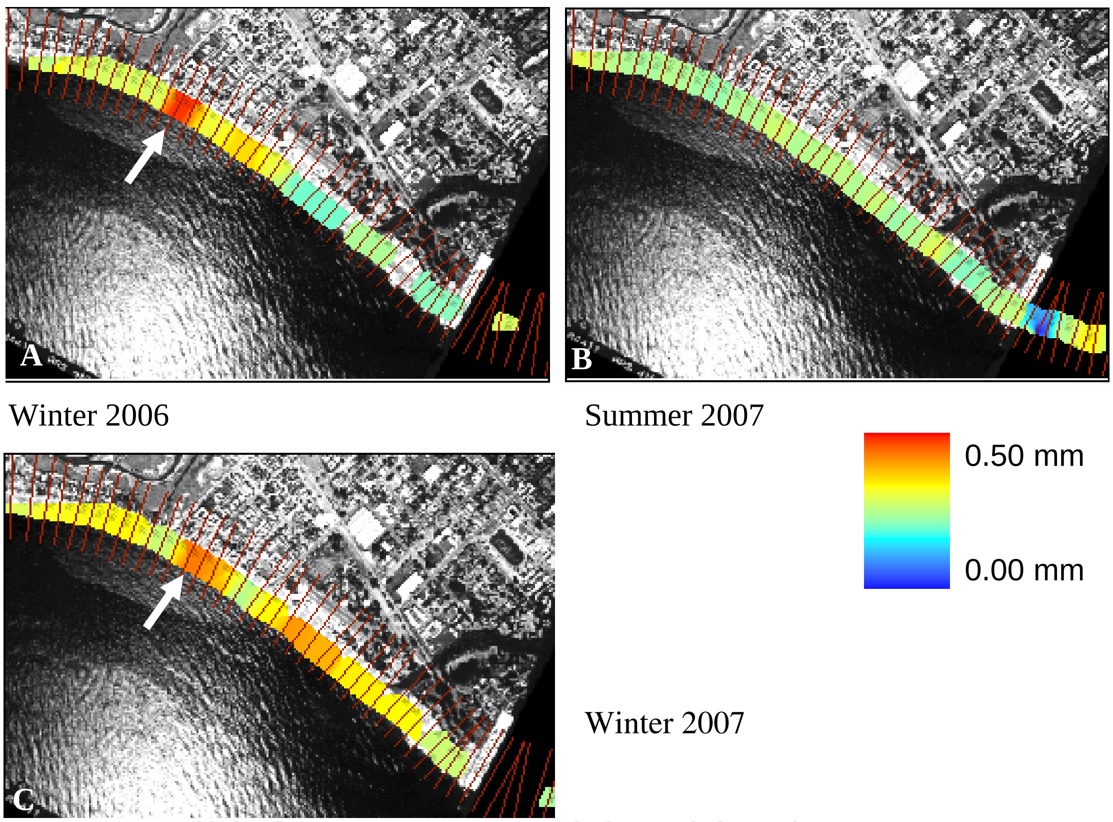

Figure 11**.** Gridded sediment grain size samples. The hotter (darker) colors represent coarser grain materials while the cooler colors represent finer grained material. A) Winter 2006, B) Summer 2006, and C) Winter 2007. Note the winter coarsening of grain sizes at the end of the revetment (arrows).

press). During the summer, grain size varied less alongshore than during the winter. The coarsest grain sizes were found during winter surveys (Figure 11) and corresponded to the area of maximum erosion downdrift of the revetment (Figure 9, 10B).

DISCUSSION

The significant reductions in impounded beach volumes that occurred during harbor construction are one major factor of Carpinteria shoreline and infrastructure vulnerability. This led to the erosion of updrift sand dunes and mostly likely to nearshore sand deposits. However following the construction of a revetment after the 1982-83 El

Niño event, the erosion hotspot shifted onto the City Beach, causing a recurring erosion hotspot. As the beach fronting the City of Carpinteria has become more important to the overall sand volume, the economic importance of this beach as a location for tourists seeking a beach experience is limiting potential erosion mitigation strategies.

Beach profile changes (1987-2005) indicate that over the 18-year time period, there has been an overall flattening of the subaerial profile with the MLLW shoreline more variable than the MSL shoreline. One potential explanation can be seen in historic ground photos documenting a loss of cobble-sized material from the beach during the 1997-98 El Niño event (Barnard *et al.* in press). Another potential explanation could be the construction of a winter beach berm to protect oceanfront properties from flooding and erosion. The impacts of this practice are not well understood, although the net effect of the practice is to artificially move the shoreline position landward in the late fall, and seaward in the spring. This practice may artificially distribute sand lower on the profile.

Carpinteria exhibits alongshore variability in beach width, volume, and shoreline response. The erosion of the beach in the west, and the accretion of the beach in the east can be seen in both of the last major El Niño events. This El Niño rotation pattern matches observed long term shoreline changes which differs from the seasonal pattern which is more uniform alongshore (Figures 9 & 10). Much of the alongshore variability can be explained by the impacts of anthropogenic alterations to the coastal system. The difference between the two El Niño events, though, is the migration of the erosion hotspot to the City of Carpinteria beach, following the construction of the revetment. Evidence for this anthropogenic impact is shown by the relatively stable beach widths along the unarmored portions of the Carpinteria beach. The accretion "trend" seen in the back beach at Transects 760-770 (Figure 6) is caused by the placement loss or encroachment of a revetment onto the beach that has artificially advanced the back beach. Furthermore, volume change, profile change, shoreline change, and beach width all indicate that winter erosion for the entire Carpinteria shoreline peaks just downdrift of the revetment, making this area the most susceptible to winter storm waves and flooding. This peak in erosion is likely due to the classic end around effects from the structure, which cause acceleration of longshore currents and increased sediment suspension and thus removal of sediment from in front of the structure. The presence of and regional of sediment coarsening hotspot (Figure 11A & C) co-located with this erosion hotspot (Figures 9 &10) provides sedimentological evidence for the increased scour.

The highly significant correlations between the dredge volumes and beach volumes is somewhat expected given the impacts of sand impoundment and the erosion wave in the 1930's. The four-year lag time between harbor dredging and sand volume changes is relatively consistent with the findings of Bailard (1982) who examined winter beach widths and dredge volumes and found a peak lag at 5 years. Given the highly energetic El Niño winters of 1982-83 and 1997-98, it is likely that this may have increased the average longshore sediment transport rate. The peaks in the correlation analyses are reached at 4 years, but remain positive and significant up to the 10-year lag (Barnard in press). This may indicate that the sand volumes dredged from the harbor continue to reach Carpinteria for 10 years following dredging. Another plausible explanation is that much of the sand transport is done during a few energetic years interspersed with calmer years and leads to an average arrival time of 4 years.

CONCLUSIONS

The evolution of Carpinteria is a story of a manmade coastal disaster. Sand impoundment caused by the construction of the Santa Barbara Harbor in the late 1920s created an erosion wave that impacted downcoast Carpinteria. Historic subaerial beach volumes declined by more than 175,000 m^3 following the erosion wave, which was likely related to the decline in nearshore and beach sand deposits near Sand Point. The initial erosion wave dramatically reduced beach widths by 50 m. While some recovery has occurred, a recurring hotspot downdrift of a revetment requires regular beach maintenance and periodically threatens oceanfront property during storm events. Beach volumes at Carpinteria have been found to significantly lag the Santa Barbara harbor dredge volumes with a 4+ year travel time.

Using a combination of historic air photos, lidar, and physical measurements,historic shoreline and beach width changes were analyzed spanning the last 138 years. The long-term beach width and shoreline change analyses show preferential erosion (-0.35 m/yr) at the updrift end of Carpinteria and accretion downdrift (+0.3 m/yr). The coastal has evolved by rotating with the updrift west end narrowing ~50 m while the downdrift eastern end of the beach has widened 40 m over 1869-2006 time period. El Niño storm impacts measured before and after the 1982-83 and 1997-98 El Niño events are shown to have a rotation pattern similar to the 138-year long-term shoreline change rates. Between 1983 and 1985, following the 1982-83 El Niño event, construction of a revetment at the western end of the beach was completed. Analyses following the 1997-98 El Niño event show that the erosion hotspot, present following both events, had shifted downdrift to its present location on the City of Carpinteria beach.

The erosion hotspot adjacent to the east end revetment on the City of Carpinteria beach is reflected in the analysis of shoreline position, beach widths, volume change and profile change. Seasonal sediment sampling shows that there is a coarsening and increase in alongshore variability of sediments in the winter with the coarsest materials co-located with the erosion hotspot. This evidence suggests that the current hotspot is related to the construction of the revetment. However, the predictable El Niño event rotation pattern, the 138-year long-term shoreline change rates, and the 77-year long-term beach width changes provide evidence that El Niño events also play a major role in shaping the coastline of Carpinteria. The challenge ahead is whether the city can identify an erosion mitigation strategy to resolve this erosion hotspot without sacrificing the beach amenities that drive this coastal economy, or continue to shift the erosion hotspot downdrift.

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