Final Draft Report
Subject to Revision

California Coastal Erosion Response to Sea Level Rise - Analysis and Mapping

Prepared for the

Pacific Institute

Prepared by

Philip Williams & Associates, Ltd.

March 11, 2009

Project Study Area

Houses in Isla Vista threatened by Sea Cliff Erosion. June 2006
Photo by David Revell

Waves flooding ocean front road in Santa Cruz, February 2008
Photo by David Revell

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1. INTRODUCTION

1.1 STUDY PURPOSE AND SCOPE

This report documents future coastal erosion hazards and the methodology used to estimate potential erosion, as part of the Coastal Infrastructure and Vulnerability Assessment Project. The study provides estimates of coastal erosion hazards for the California coast from Santa Barbara to the Oregon border. In addition, PWA compiled a statewide base flood elevation layer to support a flood analysis by the Pacific Institute (Pacific Institute 2009). This erosion methodology is applicable to other areas along the west coast of the United States, and was developed to be modular so that updated estimates could be more rapidly accomplished with improved data and refined methods.

We have also submitted digital GIS shapefiles representing future coastal erosion hazard zones for cliff backed and dune backed coastal areas for 2025, 2050, 2100. For each of these planning horizons, we projected future coastal erosion hazards based on a high (1.4m) and a low (1.0m) sea level rise scenario provided to us by the Scripps Institute of Oceanography (Scripps) (Cayan *et al.* 2008). The erosion hazard zones are intended to provide input to the Pacific Institute for its evaluation of the limits of future coastal erosion and flooding and associated economic impacts. PWA also tabulated the 100-year coastal flood elevation for the entire California coast using elevations published by the Federal Emergency Management Agency (FEMA), including estimating elevations for coastal reaches without published values. A second estimate of the “100-year coastal flood” elevations was accomplished for the study area based on detailed analyses of modeled water levels and waves. These two coastal flood elevation estimates are approximate but also some of the only estimates available for most of the California coast.

These erosion and flood estimates produced by this study are an approximate but unique quantification of the significant hazards facing coastal California. This report is intended to inform the State of California in its adaptation planning to climate change. This study is also a basis from which local communities and Federal Agencies can prioritize more detailed studies to satisfy their responsibilities in coastal zone management.

This is a Final Draft, and is therefore subject to revision. Comments may be provided to the authors. This Final Draft incorporates revisions resulting from an independent peer review, completed in December 2008 to January 2009.

1.2 BACKGROUND

Climate change may affect many aspects of California, including water supply, flooding, recreation, and ecology with sea level rise a major concern. In addition, sea level rise is expected to increase coastal erosion and flooding hazards along the California coast. Other aspects of climatic changes, such as increased wave heights and storm activity, could exacerbate the effects of higher sea level. The rise in sea level itself will not only drown existing beaches and shores, but it will also result in a recession of the shoreline landward, thereby endangering public and private resources.

Several prior studies have looked at the effect of sea level rise on the coast, but only in terms of the limits of inundation over the static landscape (BCDC, 1988, 2008; San Diego Foundation, 2008; USGS, 2008). However, we can expect the coast to adjust as increased water levels change the location of wave action and sediment transport, resulting in erosion and re-contouring (Bruun 1962; PWA 1985). Understanding that sea level rise is more than just inundation is especially important in California. Much of the California coast is geologically young and uplifted, and therefore includes a steep rise in elevation within and near the coastline. Specifically, there is significant development close to the edge of cliffs that are above the elevation of the 100-year flood (e.g., FEMA flood maps). Therefore, increasing this flood elevation and noting the change in inundation may not show much damage potential along cliff backed shorelines. However, much of this coast continues to erode and experienced loss of land and damages in the recent past which can be expected to increase in the future with or without sea level rise. Hence, inundation mapping alone under-predicts the impact of sea level rise to the coast. For this reason, PWA undertook predicting potential future erosion for a range of sea level rise scenarios. While many site specific efforts to document erosion have been made, this work represents one of the first systematic evaluations of coastal erosion hazards for the majority of the California Coast.

This study was done in cooperation with the Pacific Institute who conducted flood mapping and a vulnerability assessment based on future sea level rise. This report (1) describes the methodology used by PWA to evaluate Base Flood Elevations used by the Pacific Institute and to estimate the coastal erosion impacts and (2) addresses the management question: how far inland could the coastline recede under a given sea level rise scenario?

PWA was supported by Scripps which provided the future water level and wave time series output from a Global Climate Model (GCM), driven by a range of climate change scenarios (National Center for Atmospheric Research scenarios A2 and B1) (Cayan *et al.* 2008). PWA was also supported by the Coastal Data Information Program (CDIP) which provided wave transformation modeling (O’Reilly et al. 1993; O’Reilly and Guza 1993; CDIP 2008) to convert the deep water wave data (output from the GCM) to refracted, nearshore wave conditions.

1.3 PROJECT PURPOSE

The purpose of this project was to map the potential erosion due to sea level rise on the Central and Northern California Coast using the best available data sets. This mapping supports a socio-economic analysis by Pacific Institute on the impact of flooding and erosion on infrastructure and property. The end result of the *Coastal Impacts and Vulnerability Assessment Project* is a first order coastal hazard and socio-economic vulnerability assessment (Pacific Institute 2009). This project also provides a quantified conceptual framework for future assessments that can be updated with new data and analysis methods, and refined for other applications such as more detailed, local assessments.

1.4 PROJECT OBJECTIVE

PWA developed a set of GIS data layers that represent a first order evaluation of the shoreline areas susceptible to climate change impacts associated with different scenarios of sea level rise, changing wave climate and wave run-up. This evaluation identified a range of hazard zones showing the minimum and maximum extent of potential erosion due to sea level rise given a likely range of climate change estimates developed by Scripps as part of the CEC funded research. PWA built on existing and developing research conducted by Scripps (Cayan *et al.* 2008), United States Geological Survey (USGS) (Hapke *et al.* 2006, Hapke and Reid 2007), CDIP, and research completed under the guidance of Dr. Gary Griggs (Griggs *et al.* 2005). We also drew upon the expertise and experience of regional scale coastal hazard investigations in Oregon (Komar *et al.* 1999; Revell *et al.* 2002; Ruggiero 2008) , Texas (Leatherman 1984) and the United Kingdom (DEFRA 2002).

1.5 DISCLAIMER

This product represents a first order evaluation of coastal hazards based on the currently available predictions of water levels and wave conditions, and interpretations of sea level rise, shoreline change rates, and geomorphic conditions. Available methods and data are not sufficient to model coastal erosion with high confidence. The budget and schedule for this analysis were also constraints to the level of accuracy and detail. Therefore, the hazard zones herein are considered appropriate as a "first order estimate" to inform planning, adaptation strategies, and future study. The methodology used to develop the hazard zones was kept relatively simple and modular to facilitate understanding and future application with minimal effort. This work shall not be used to assess actual coastal hazards, insurance requirements or property values, and specifically shall not be used in lieu of Flood Insurance Studies and Flood Insurance Rate Maps issued by FEMA.

Consequently, any use of the hazard zones except for the purposes described herein are at the user's sole risk and is not authorized by PWA. We believe the estimates overall provide a meaningful basis for a "first order representation" of the problem and provides useful information as a management tool. Future data collection and study are needed to improve these erosion projections with specific recommendations discussed in Section 6.

1.6 SPATIAL EXTENT

The study region stretches approximately 1450 km or 900 miles and covers most of the Central and Northern California coast from the Oregon border in the north, around Point Conception to Santa Barbara in the south. This region covers the California portion of the California Current Large Marine Ecosystem. This study area represents the least developed portion of the state and the most likely to allow the natural processes of coastal erosion to occur. The extensive armoring and beach nourishment in southern California inhibits recession of the back shore and natural processes of erosion.

Many of the geological units in the study region are susceptible to various forms of landslides. These landslides are difficult to predict both in terms of failure size and the mechanism. It is important to note that these landslides are likely to be exacerbated by sea level rise. Certain areas like Big Sur (Monterey County) and Devil's Slide (San Mateo County) currently have ongoing construction to combat erosion, and were only included in this study to the extent that published erosion rates were available.

The majority of the southern California coast was excluded due to the myriad ongoing initiatives focused on climate change and hazards mapping. Large research projects are currently underway by the U.S. Geological Survey, Scripps, and the CEC among others. These research efforts are likely more in depth than the first order erosion representation intended by this study. Given the economic values of the infrastructure and industries at risk in southern California, it is likely that shoreline management will include the strengthening of existing armoring and sand nourishment to retain beaches. These management actions would alter the natural processes and reduce the applicability of this study. While our methodology could be applied to armored shorelines (both "hard" structures such as a concrete seawalls and "soft" structures such as widened beaches), the potential range of scenarios could be expanded significantly owing to the dependence on human actions and the lack of consensus on the long-term effects and effectiveness of coastal armoring. Tackling these issues was not practical within the schedule and budget constraints of this project.

Finally, while the California Coastal Commission has mapped the locations of shoreline armoring, the lack of readily available information on the status, height, condition and life expectancy of these structures makes predicting future erosion difficult. Furthermore, new shore protection is likely in general but difficult to predict specifically. The methodology does not address the effects of future armoring on erosion.

2. METHODS

2.1 GENERAL APPROACH

In this study, we have estimated the erosion “response” to climate change characterized in terms of sea level rise and changing wave climate. In reality, coastal erosion is a complex response to many processes (and forcing parameters) such as marine processes (water levels, waves, sediment supply and transport, etc.), terrestrial processes (rainfall, runoff, wind, etc.) and other instabilities (seismic, biologic, etc.), as well as geology and antecedent topography (Collins and Sitar, 2008; Trenhaile, 2002). This study only considers marine erosion processes and explicitly only the water level and wave forcing parameters. However, we have incorporated historic erosion rates, geology (general classification), and basic geomorphology (sandy dune or steep cliff) into our methodology to implicitly include other processes and parameters. The incorporation of historic erosion rates (Hapke *et al.* 2006, Hapke and Reid 2007) into the methodology helps to integrate local site conditions and provides a peer –reviewed systematic statewide data set upon which to extrapolate.

The hypothesis for this study is that sea level rise will affect the Total Water Levels (TWL) increasing the amount of time that the waves impact the backshore resulting in an increase in erosion (Figure 1). TWL is a water elevation determined by the sum of mean sea level, tides, waves and wave run-up, and affected by other storm components including surge, and atmospheric forcing such as El Niño events (Ruggiero *et al.* 1996, Ruggiero *et al.* 2001). TWL has also been identified as a key parameter in quantifying coastal flood hazards and the implications of climate change on the Pacific Coast of the United States (Ruggiero *et al.* 2001, FEMA 2005, MacArthur *et al.*, 2006, Ruggiero 2008). The TWL is shown schematically in Figure 1.

The exceedance of TWL above the elevation of the toe junction has been related to erosion (Sallenger *et al.* 2002, Ruggiero *et al.* 2001, Hampton and Griggs, 2004, FEMA 2005). A simple conceptual index was used to relate TWL and erosion: the extent that total water level (in terms of frequency and height) exceeds the elevation of the back beach or toe of cliff. Our intention was to use total water levels representing current conditions, and compare them with recent erosion rates. The five critical components to our methodology are a time series of total water levels, erosion rates, geology, backshore type (i.e. dune or bluff), and elevations of the backshore toe junction. Since total water levels and coastal geology vary along the coast of California, the analysis was applied at a number of locations based on the nature of the various components.

This approach includes the geomorphology of the backshore areas (geology and elevations), while using a forcing parameter (total water level) that integrates future water levels and waves. Extreme high water levels and waves are partially correlated due to the forcing of storms and climatic conditions such as El Nino. The time series of ocean water levels coupled with the wave conditions were outputted from a Global Climate Model at San Francisco and Crescent City (Cayan *et al.* 2008). These coincident time series were used to calculate TWL time series to force future erosion. By using coincident time series of water levels and waves to calculate the TWL, the joint probability of occurrence of high water levels and waves is fully considered without needing to separately define the joint probability (Garrity *et al.*, 2006). Tides and wave exposures vary with latitude, so deep-water conditions were characterized regionally for three sites – Point Conception, San Francisco and Crescent City (Cayan *et al.* 2008.) Because waves are affected by shoreline orientation, wave exposure, depth and depth contours, the deep water wave time series were transformed by Dr. Bill O'Reilly's refraction model to 140 nearshore locations identified by PWA along the coast (CDIP 2008; O'Reilly et al, 1993; O'Reilly and Guza, 1993).

At the shoreline, coastal geology and topography especially beach slopes become very important in wave run-up and TWL. To account for the diversity of conditions, PWA divided the coastline based on geology type then further subdivided the coast into ~4,100 block segments. These subdivided blocks were attributed to an offshore baseline along with necessary input parameters such as the wave refraction nearshore locations, historic erosion rates, and various geomorphic elevations and slopes. Using the combination of tides, sea level rise and wave run-up, TWL was calculated for each segment along the coast. Future erosion rates and distances were then calculated for each block segment for the range of climate change scenarios at three planning horizons. This resulted in a range of estimated future dune and cliff top locations for each of the several thousand block segments. These locations measured inland from the offshore baseline were used to define coastal erosion hazard zones. These hazard zones were provided to PI for their use in geospatial analysis, primarily to determine the areas of different land types and development impacted, and the associated potential direct economic costs. This methodology and methods are explained in more detail in subsequent sections.

In applying our methodology, PWA evaluated the following geomorphic and coastal process variables:

- Wave run –up
- Wave Sheltering
- Total Water Level elevations
- Historic Erosion Rates
    - Cliff shorelines
    - Sandy shorelines
- Geology
- LIDAR Topography
- Beach slopes
    - Foreshore (between Mean Sea Level and Mean High Water)
    - Shoreface slope (between 10m depth to the back of the beach)
- Flood Elevations

Overall the general methodology for the erosion hazard mapping can be seen in Figure 2. The basic premise of this first order representation was to utilize appropriate available information to characterize the California coast and evaluate potential future erosion by examining changes to a time series of total water level elevations that exceeded the elevation of the back-beach. Our underlying assumption is that erosion will accelerate as sea level rises and waves become more powerful with climate change. The higher water level results in greater wave energy being dissipated higher up on the shoreline and directly onto the face of cliffs and dunes. This methodology was technically reviewed at various points in time by a panel of experts who provided timely input on decisions necessary for implementation.

2.1.1 Data sets

- **Sea level rise scenarios** generated from Global Climate modeling efforts from Dan Cayan and others at Scripps Institute of Oceanography (Cayan *et al.* 2008). In particular, this data set contained two still water level time series from San Francisco and Crescent City. The "high scenario" was based on the NCAR CCSM3 scenario SRESA2 (1.4m rise by 2100) adjusted for effects of dams and the "low" scenario based on the NCAR PCM1 scenario SRESB1 (1.0m rise by 2100) which was not adjusted for effects of dams (provided by Scripps).

- **Wave time series** from Scripps were derived for deepwater winter waves from the same GCM output for three sites (Point Conception, San Francisco, and Crescent City) (Cayan *et al.* 2008) and run through 140 CDIP nearshore wave transformation (MOP – Monitoring and Prediction; CDIP 2008) sites (provided by Dr. Bill O'Reilly of CDIP). The MOP system was in "beta" mode at the time, and therefore this project is one of its first large scale applications.

- **USGS – Coastal erosion rates** from the National Assessment of Shoreline Change in California. These data include: Long term linear regression rates (LRR) for sandy shorelines (1870s to 1998; Hapke *et al.* 2006), and end point rates (EPR) for cliff backed shorelines (1930s to 1998; Hapke and Reid 2007) along with the1998 cliff edge delineation used in Hapke and Reid (2007). (provided by USGS)

- **Foreshore Beach slopes** – Mean High Water slopes based on the Stockdon *et al.* 2002 method. These were originally generated to correct the proxy datum offset problems in Hapke *et al.* 2006 (provided by USGS and Dr. Peter Ruggiero).

- **Geology** – data originally from California Geological Survey updated by Griggs, Patsch and Savoy 2005 (provided by Dr. Kiki Patsch).

- **Shoreline Inventory –** data originally collected in Habel and Armstrong 1978, digitized by Melanie Coyne in 1999, and updated by Griggs, Patsch and Savoy 2005 (provided by Dr. Kiki Patsch).

- **LIDAR** – April 1998, October 2002 – NOAA, NASA, USGS (provided by NOAA Coastal Services Center). Note that the primary data set was April 1998, originally collected to evaluate the storm impacts following the 1997-98 El Niño. The 2002 data set was completed to fill gaps in the 1998 data set, and is only used when the 1998 data are unavailable.

- **Bathymetry** – 10 m contours of the California bathymetry (provided by California Department of Fish and Game). This was used to identify a shoreface beach slope by examining the distance from the 10m depth contour to the toe of the backshore.

2.1.2 Total Water Levels

As mentioned earlier, TWL is a water elevation determined by the sum of mean sea level, tides, waves and wave run-up, and other components including nearshore currents, storm surge, and atmospheric forcing such as El Niños (Ruggiero *et al.* 1996, Ruggiero *et al.* 2001). The TWL is shown schematically in Figure 1 Existing data sets were used to develop TWL for each Backshore Block (described in more detail in Section 2.1.3).

The sea level rise scenarios received from Scripps represented a 100-year time series of the still water levels (tides and sea level rise) at two locations – San Francisco and Crescent City (Figures 3 and 4; Cayan et al 2008). Accompanying this still water level data were deep water wave data for three locations – Pt. Conception, San Francisco, and Crescent City. Since the wave data supplied by Cayan et al (2008) were derived for deep water, the data did not account for localized differences in wave climate and shoreline exposure. To gain a better understanding of the effect of shoreline orientation, wave exposure and wave refraction, PWA coordinated with Dr. Bill O'Reilly of CDIP who conducted the nearshore wave transformations from the three deep water wave sites to 140 nearshore locations. The nearshore sites are part of the CDIP Monitoring and Prediction (MOP) system (CDIP 2008), which provides public access to monitoring-based wave predictions (see Appendix 1 for description). The deep water waves at Point Conception were applied to estimate waves at nearshore sites in Santa Barbara (SB) and San Luis Obispo (SL) Counties along with the San Francisco water levels. San Francisco deepwater waves were applied to estimate waves at Monterey (MB), Santa Cruz (SC), San Mateo (SM), San Francisco (SF), Marin (MA) and Sonoma Counties (SO) along with San Francisco water level values. Crescent City deepwater waves were used to evaluate localized waves in Mendocino (ME), Humboldt (HU), and Del Norte (DN) Counties along with Crescent City water level values (Table 1). For each backshore block, PWA attributed the most similar MOP site and the 100 year TWL elevation.

Table 1. Summary of Maximum Deepwater Wave Sites and 100-Year Wave Characteristics for Each Region

Location					Maximum TWL		
Deepwater Wave Sites	**Counties**	**100-yr TWL (ft NAVD) (m)**	**MOP ID**	**MOP**	**Ho' (ft) (m)**	**Tp (sec)**	**SWL (ft NAVD) (m)**
Crescent City	DN, HU, ME	35.1 (10.7)	DN0045	Klamath Spit	39.8 (12.1)	19	7.2 (2.2)
San Francisco	SO, MA, SF, SM, SC, MB	32.1 (9.8)	SM200	Martins Beach	34.4 (10.5)	17	5.3 (1.6)
Point Conception	SL, SB	29.9 (9.1)	B1270	Point Arguello	23.9 (7.3)	19	6.3 (1.9)

Notes: Ho' is the deepwater equivalent wave height; Tp is the peak wave period; SWL is the still water level for each MOP site. Note that the 100 year TWL was calculated for each block. The results above show the most extreme values for each of the Deepwater wave time series.

After receiving the nearshore transformed wave time series from CDIP, PWA then calculated a wave run up time series at each "block" segment (defined in section 2.1.3) using the wave run-up equation of Stockdon *et al.* 2006. Inputs to the wave run-up equation were the foreshore beach slope calculated by the USGS using the methodology in Stockdon *et al.* 2002 and the transect data extracted from LIDAR. This wave run-up time series was then added to the still water levels (SWL) to provide a time series of total water levels (TWL= run-up + (SWL(sea level rise)) at each site.

Using this time series we calculated the amount of time that these TWL exceeded certain elevations. This produced a series of exceedance curves for each of the individual backshore blocks. An example of one TWL Exceedance Curve for a particular location (Jalama Beach just north of Point Conception) and range of sea level rise is shown in Figure 5. Figure 6 compares TWL exceedance curves for the extreme sites showing the range of wave exposures for exposed vs. sheltered sites. This figure shows the TWL calculated for existing conditions and with an estimated 100 year rise of sea level rise.

For each of the nearly 4100 blocks, the appropriate tide station Sea Level Rise (SLR) data were assigned adjusting the MSL2000 from the GCM to NAVD88. This set the base year of the analysis at Year 2000. A unique set of 10 frequency exceedance curves at 10 year intervals was calculated between 2001 and 2100 for each block so that changes in exceedance frequency could be evaluated over various planning horizons. To examine changes over time, the block averaged elevation of the toe (Et) was compared with the frequency curve to determine the present TWL exceedance frequency (Pe) at that elevation, and the intensity of exceedance, as the height (TWL-Et). This procedure was repeated for each sea level rise scenario and each block with slightly different methodologies taken for the various backshore types – dunes or cliffs.

2.1.3 Backshore Characterization

We used the data sets bulleted in section 2.1.1 above to characterize the California coastline into dune and cliff backed shoreline segments. This classification was attributed in GIS to an offshore baseline roughly corresponding with the shoreline inventory of Habel and Armstrong (1978) that was digitized by Melanie Coyne in 1999. This baseline layer was also attributed with an updated coastal geology layer generated during the update of Griggs et al 2005. This backshore baseline layer was divided based on geologic units. For each continuous geologic unit we further divided the geologic units into 500m individual blocks (Figure 7). Approximately 2,500 cross shore profiles were extracted from the 1998 LIDAR in ArcGIS© and interpreted using a custom built tool in MATLAB© to identify toe elevations (Et), foreshore beach slopes, and cliff and dune heights. Attributes needed to drive the erosion models were calculated at the block scale in GIS and attributed to the backshore characterization line layer. The list of attributes collected included:

- Block ID #
- Unit ID #
- Geology Type
- Toe Elevation (Et)
- Cliff/Dune edge elevation
- Cliff/Dune Height elevation
- Slope Cliff/Dune Face
- Foreshore beach slope
- Shoreface beach slope (10m to Toe elevation)
- Nearshore MOP site ID
- Tidal Correction from climate model MSL to nearest tidal station NAVD88
- 100 year TWL event
- Shoreline Change Rate – Sandy Shore linear regression
- Shoreline Change Rate – Cliff Edge end point rate
- Standard deviation of geologic unit averaged shoreline change rates
- Offset distance between baseline and reference line

We ground-truthed this data set to the extent practical using a combination of site investigations, oblique air photos from the California Coastal Records Project (www.californiacoastline.org), and topographic information extracted from the 1998 post El Niño LIDAR flight. We conducted several iterations of quality control to check the attributed parameters. However future work on collecting a range of these various attributes (e.g. toe elevation, slopes, top-of-cliff elevation) would likely improve the estimated future erosion rates and distances.

Following the initial block averaging of existing data sets, only 55% of the blocks had the full suite of input values necessary to run our erosion models (Table 2). To provide for more complete coverage along the coast, PWA prioritized the following criteria to fill in missing data gaps for the 500m spaced blocks (see Table 2):

1. Use the block averaged data when available
2. Use the same geologic unit averaged data that is continuous with the missing blocks
3. Use the PWA block averaged LIDAR interpreted transect data
4. Use the PWA unit averaged LIDAR interpreted transect data
5. Use geologic unit averaged data found in relatively close proximity (+/- 20km)
6. For missing cliff toe elevations (Et), revisit LIDAR to collect additional toe elevations

In lieu of further refinement beyond the scope of the study, the following outlying "filters" were used to identify and eliminate seemingly unrealistic values and values not well handled by the methodology:

Filters

1. Remove all toe elevations > 6m
2. Elevate all toe elevations <1.0 meters up to 1.0 m
3. Remove all beach slopes > 1:4 (height:length)
4. Remove all long term accretion trends >1.5 m/yr

Table 2. Summary of the Backshore Characterization Comparing Raw USGS Published Data Following Application of PWA Filtering Criteria

	Length (km) (miles)	Total # of blocks	USGS coverage (# of blocks)	USGS % of shore	PWA study (# of blocks)	PWA % of shore
Cliff	1142 (710)	3276	1607	49.1%	2897	88.4%
Dune	303 (188)	816	634	77.7%	764	93.6%
Total	1445 (898)	4092	2241	54.8%	3661**	89.5%*

* Majority of gaps in block data after filtering were found along the Lost Coast and Big Sur
** This represents blocks where all necessary input parameters enabled calculation of hazard zones

2.1.4 Dunes

The dune erosion hazard zones were generated using a three step methodology. First, the inland shoreline retreat was estimated based on the increased total water level associated with predicted climate change. Second, the historic erosion rate was applied for the planning time horizon to get the projected baseline erosion. The third step added the storm-based recession associated with a 100 year storm event. Both the shoreline retreat (step 1) and the 100 year storm event (step 3) were predicted using the geometric model of dune erosion proposed by Komar *et al.* (1999) and applied with different slopes to make the model more applicable to sea level rise instead of storm response.

For evaluating the sea level rise impacts (step 1), the future toe elevation was established based on the new total water level exceedance curve, assuming the percent exceedance of the TWL above the toe stayed constant. This was done by moving vertically up from the existing exceedance curve to the future exceedance curve along the percent exceedance value (Pe) to intersect at the future toe elevation (Figure

8). This determined the future elevation of the toe at the specified planning horizon. This future toe elevation was turned into a recession distance by using the average slope of the shoreface calculated from the 10m contour to the elevation of the back beach (Bruun 1962, Everts 1985). Finally, the erosion of the toe extended inland through the dune at a standard angle of repose of 32°, the angle of stability for dry sand, to the dune height extracted from the LIDAR transects.

Long term historic shoreline change rates were included to take into account the variety of additional factors such as sediment budget and local geomorphic controls (part 2). In some cases, these change rates showed long term accretion and other localized erosion hotspots. Since the last date used in the USGS shoreline change study was Spring 1998 following the 1997-98 El Niño, the post El Niño LIDAR data represent an eroded shore (see discussion under limitations Section 5.2). To minimize the influence of any errors associated with the use of the 1998 LIDAR, PWA averaged data extracted from the USGS and the LIDAR data over each continuous dune stretch. This was done in an effort to reduce the influence of the heavy flood and erosion event that occurred just prior to the 1998 LIDAR collection with its documented impacts of erosion hotspots and large scale beach rotations (Revell *et al.* 2002; Sallenger *et al.* 2002, Hapke et al. 2006). It was assumed that these localized erosion and accretion signals would be muted as sand dispersed over time along the same stretches of coast that the averaging occurred.

The maximum 100-yr TWL was selected for each region based on the county groupings shown in Table 1 (Section 2.1.2). The forcing parameters (Ho', Tp, and SWL) associated with the 100-yr TWL event were extracted from the modeled time series at each MOP site and calculated using beach slopes from each block. The values in Table 1 are samples of the larger data set of estimates calculated for each block.

Finally, to add the impacts of a storm event at the end of each planning horizon, we evaluated the impacts of the 100 -year storm event at the end of each time period using the geometric model of foredune erosion (part 3; Table 1) (Komar *et al.* 1999; FEMA 2005). This model uses a foreshore slope to convert the TWL to a new toe location, from which an angle of repose is assumed to extend upward to daylight through existing dune topography. The results of these three steps were added together to calculate the Dune Hazard Zone (DHZ).

2.1.5 Cliffs

Our methodology for predicting the Cliff Erosion Hazard Zones was to increase the historic cliff erosion rates based on the relative increase in time that the total water level exceeded the elevation of the backshore and to add an additional factor to account for variability in geology over alongshore distances. This method is an evolution of a sea level rise prediction method developed by Leatherman (1984), in which he related erosion rates to observed sea level rise rates, and then prorated future erosion rates based on predicted sea level rise rates. Our method substituted the sea level rise rate with the changes in total water elevation between planning horizons. This work builds on recent and ongoing research in Oregon and California (Ruggiero *et al.* 2001, Collins and Sitar 2008, and Ruggiero 2008).

Using the nearshore total water level exceedance curves at each block, we examine the percent exceedance between curves for present and future planning horizons to determine the change in percent exceedance (Figure 9). This was completed by identifying the current intersection of the cliff toe elevation (Et) with the exceedance curve. Then moving horizontally, the intersection with the future (next 10 year time period) exceedance curve identified the change in percent exceedance assuming a constant toe elevation. This change in percent exceedance was then used to prorate the historic erosion rate at 10 year intervals. For each interval, the prorated erosion rate was turned into a recession distance by multiplying the new prorated erosion rate by the 10 year interval. The overall erosion distance was then the sum of the 10 year recession distances (e.g. Future recession distance = (R2020 x 10) + (R2030 x 10) + etc).

To account for alongshore variability within geologic units PWA added two standard deviations of the historic erosion rates for each geologic unit multiplied by the planning horizon. This alongshore variability factor was then added to the prorated erosion distances to calculate the Cliff Hazard Zone (CHZ).

3. REPRESENTATION OF EROSION HAZARD ZONES IN GIS

To represent the calculations of recession distances geographically, PWA implemented the calculations in GIS using a one-sided buffer drawn from the offshore baseline landward. Depending on whether the backshore type was a dune or a cliff, a different reference feature was mapped. The distance between the offshore baseline and the reference line was measured and then this distance was added to the hazard zone. Through this process the coastal erosion hazard zones were calculated for each block and extended from the offshore baseline inland the calculated distance.

3.1 REFERENCE FEATURES

The hazard zone representations for the dunes and the cliffs were based on different reference features. For the dunes, the reference feature was the toe of the dunes as interpreted in the ~2500 transects extracted from the 1998 LIDAR data. This reference line was drawn between the identified points on each transect. For the cliffs, the reference feature was the cliff edge extracted by the USGS from 1998 LIDAR as part of the National Assessment of Shoreline Change (Hapke and Reid 2007). This cliff edge line was generalized at 3m to smooth the line and facilitate generation of the hazard zones. These reference features differ in spatial locations from the offshore baseline created as part of the backshore characterization (see Section 2.1.3). To account for these differences, offset distances were calculated at three locations for each block – two end points and the midpoint. These offset distances were block averaged and attributed to the backshore characterization layer as a distance. After calculating the inland hazard zone distances, these offset distance were then added (or subtracted) to define the inland limit of the erosion hazard zone.

3.2 HAZARD ZONE BUFFERS

The hazard zones were generated using a one-sided buffer in ESRI's ArcINFO®. The buffering procedure moves along each block segment and generates a new line that represents the most distant point drawn from the radius of a circle. In this case the radius is equal to the sum of the offset distance and the hazard distance. The starting line was the offshore baseline representing the backshore characterization layer (see section 2.1.3). As a result, the hazard zones often appear to have steps on the inland side which represents the differences in input values used in the hazard zone calculations (Figures 10b and 11b). The buffer zones drawn for each block were then dissolved to minimize the automated generation of additional spikes and additional hazard zones. This results in a single hazard zone for each planning horizon (i.e. 2025, 2050 and 2100) and each scenario (B1 - 1m rise in sea level by 2100; A2 -1.4 m rise in sea level by 2100).

3.2.1 Base Flood Elevations and 100-yr Total Water Levels

To support Pacific Institute in evaluating flood hazards associated with sea level rise, Base Flood Elevations (BFEs) published by FEMA were collated into a GIS-based shapefile, and attributed to an offshore line paralleling the shoreline. Digital Flood Insurance Rate Maps (DFIRMs), provisional DFIRMs, and paper FIRMs along with tabulated flood elevations in Flood Insurance Studies (FISs) for communities in the northern California region were used to populate the GIS shapefile. Substantial gaps were filled using professional judgment, informed by considering published values for nearby areas or generally by local knowledge and experience regarding wave exposure and geography. Values were adjusted to the year 2000 North America Vertical Datum (NAVD) based on land and tidal datums for regional, primary tide stations published by the National Ocean Service (NOS). The conversion and rounding process varied depending on the data source and hence accuracy varies. These flood elevations were provided to Pacific Institute, who generated flood hazard maps for their use in projecting coastal inundation and ultimately direct economic impact of a 100-year flood (Pacific Institute 2009). The intent is that both the flooding and erosion hazard zones were used to evaluate socio-economic vulnerability (Pacific Institute 2009).

Subsequently, 100-year total water levels were calculated based on the Global Climate Model (GCM) output of water level and wave time series. Since the GCM outputs included the sea level rise trends, the calculated 100-yr TWL time series were de-trended to remove sea level rise. Then, the highest value was selected to represent the 100-year TWL, which provides another estimate of the coastal BFE (FEMA, 2005). The TWL calculations included wave refraction using the CDIP wave transformation coefficients for 140 nearshore locations (see section 2.1.2). The deep water directional spectra were simplified to wave height and period after application of the transformation coefficients by integration of the transformed directional spectra. The results provide a first-order approximate estimate of the coastal flood plain with a 1% chance of occurrence (100-year flood) for the coast of California from Santa Barbara to Oregon. A unique elevation was calculated for each of the 140 nearshore sites with wave transformation (refraction) coefficients. Wave run-up was calculated with the block averaged foreshore beach slopes.

This methodology is consistent with the FEMA Guidelines for Pacific Coast Flood Studies (FEMA, 2005), but was not accomplished with the care and precision needed for a FEMA FIS and DFIRM. Note also that the source of the data is a global climate model, and we have not compared the model data with real data which was a part of the Scripps quality assurance project (Cayan et al 2008). Hence these calculations are unique and provide useful estimates of flood elevations but are not for flood risk assessments, insurance or building methods and in general should not be used or relied upon by others without prior written consent (see disclaimer).

4. RESULTS AND DISCUSSION

Results are depicted spatially in the GIS shapefiles and summarized here. Extensive discussion and analysis of results including was beyond the scope and budget of this project. Example results are shown in Figures 10b and 11b for two locations. Figures 10a and 10b are conceptual section views that correspond to the plan view for dunes (Figure 10b) and cliffs (Figure 11b). Even though land features are visible and the hazard zones are discrete, the reader is reminded that there is large uncertainty and should not be used to assess risk at a specific location (see disclaimer Section 1.5). These GIS shapefiles are not to be used without prior written consent from PWA.

The following tables provide summary data that are considered reasonable approximations of the potential extents of erosion hazards that could result if the modeled climate change occurs. The reader may want to consider the potential extent of impacts separate from the tabulated time frame, as the timing is less certain than the impact itself. In other words, a given rise in sea level is likely to happen while the time frame for the sea level to reach that particular level is less certain. Also, erosion may lag sea level rise.

Table 3. Miles and fraction of coastline studied for the erosion hazard study, by county.

County	Studied	Total	% Studied
Del Norte	42.7	49.7	86%
Humboldt*	72.9	123.3	59%
Marin	69.5	75.2	93%
Mendocino	145.5	151.4	96%
Monterey*	94.4	132.0	71%
San Francisco*	7.5	8.8	85%
San Luis Obispo*	77.0	102.6	75%
San Mateo*	57.8	59.6	97%
Santa Barbara*	84.4	116.5	72%
Santa Cruz	46.0	46.0	100%
Sonoma	63.0	68.9	91%
Total	760.7	934.1	81%

* The largest gaps in the % studied are related to areas of little data availability which include: Humboldt – Lost Coast; Monterey and San Luis Obispo – Big Sur coast (primarily terrestrial process dominated; Santa Barbara – stretches of coast that fell outside the study area.

The erosion hazard zone totals 41 square miles within the 11 coastal counties evaluated in this analysis (Table 4). There is significant variation in the areas at risk of erosion.

Table 4. Erosion area with a 1.4 m sea-level rise, by county.

County	Dune erosion miles^2 (km^2)	Cliff erosion miles^2 (km^2)	Total erosion miles^2 (km^2)
Del Norte	1.9 (4.9)	2.6 (6.7)	4.5 (11.7)
Humboldt	3.7 (9.6)	2.4 (6.2)	6.1 (15.8)
Marin	1.0 (2.6)	3.7 (9.6)	4.7 (12.2)
Mendocino	0.7 (1.9)	7.5 (19.4)	8.3 (21.5)
Monterey	1.9 (4.9)	2.5 (6.5)	4.4 (11.4)
San Francisco	0.2 (0.6).	0.3 (0.8)	0.5 (1.4)
San Luis Obispo	1.4 (3.6)	1.5 (3.9)	2.9 (7.5)
San Mateo	0.8 (2.1)	2.4 (6.2)	3.2 (8.3)
Santa Barbara	0.6 (1.6)	1.9 (4.9)	2.6 (6.7)
Santa Cruz	0.9 (2.3)	0.9 (2.3)	1.8 (4.7)
Sonoma	0.6 (1.6)	1.6 (4.1)	2.2 (5.7)
Total	14 (35.7)	27 (70.6)	41(213.8)

As discussed previously, dunes and cliffs will exhibit differential responses to rising sea levels. Our results indicate that cliffs will erode an average distance of about 66 m by the year 2100 (Table 5). In some areas, however, erosion is projected to be much higher. In Del Norte County, for example, cliffs may erode a maximum distance of 520 m. Cliff erosion is much less severe in the other counties along the coast, although still significant. Dunes exhibit much less resistance to erosion. On average, dunes will erode about 170 m by 2100. In Humboldt County, for example, dunes are projected to erode as much as 600 m by 2100.

Table 5. Average and maximum erosion distance in 2000 for cliffs and dunes, by county.

County	Dune erosion		Cliff erosion	
	Average distance (m)	Maximum distance (m)	Average distance (m)	Maximum distance (m)
Del Norte	180	400	160	520
Humboldt	160	600	61	260
Marin	140	270	110	240
Mendocino	190	440	33	160
Monterey	180	400	37	220
San Francisco	150	230	90	220
San Luis Obispo	140	330	78	280
San Mateo	230	430	31	220
Santa Barbara	190	320	54	240
Santa Cruz	170	340	36	130
Sonoma	150	320	41	190
Average	170	370	66	240

Table 6. Land lost by sea level rise scenario (High - 1.4m and Low - 1.0m)

Planning Horizon	Cliff* Land loss (acres) High to Low	Dune** Land loss (acres) High to Low	Total Land Loss (acres) High to Low
2100	15,080 to 13,340	9,620 to 6,700	24,700 to 20,040
2050	5,370 to 5,250	6,210 to 5,620	11,580 to 10,870
2025	1,420 to 1,420	5,360 to 5,320	6780 to 6740

*Cliff hazard zones include 2 standard deviations of the historic shoreline change rates calculated by block to include an additional factor of safety that is inherent in the variability of geology alongshore.
**Dune includes erosion associated with a 100-year storm event.

Table 7. Inland Distance of Erosion by sea level rise scenario (High - 1.4m and Low - 1.0m)

	Cliff*			Dune**		
Planning Horizon	Minimum Distance (m) High to Low	Maximum Distance (m) High to Low	Mean Distance (m) High to Low	Minimum Distance (m) High to Low	Maximum Distance (m) High to Low	Mean Distance (m) High to Low
2100	0 to 0	570 to 395	65 to 60	0	600 to 540	175 to 130
2050	0 to 0	175 to 170	25 to 25	0	545 to 530	130 to 20
2025	0 to 0	65 to 65	9 to 8	0	535 to 530	115 to 115

*Cliff hazard zones include 2 standard deviations of the historic shoreline change rates calculated by block to include an additional factor of safety that is inherent in the variability of geology alongshore.
**Dune includes erosion associated with a 100-year storm event.

The historic shoreline change rates for sandy shores included accretion (Hapke *et al*, 2006). We speculate that the accretion rates may not be indicative of existing conditions and therefore should be updated with new data (see Section 6. Future Work). The accretion rates were projected into the future with the effect of sea level rise subtracted from the accretion. The calculations for sandy shores may therefore under-predict the potential erosion resulting from sea level rise.

The above summary data indicate that a portion of the coast is likely to be lost to erosion over the next 100 years. This will result in the loss of private and public property and threaten or destroy existing public infrastructure such as roads and utilities. Ecological and recreational losses associated with the loss of beaches should also be expected, although the management responses to sea level rise and accelerated coastal erosion could greatly affect the extent of ecological and recreational losses.

Another interesting output of this study is the different 100-year total water level estimates. Figure 12 shows the TWL from prior FEMA studies, with the judgment-based estimates made to fill gaps in the FEMA Base Flood Elevation values (called BFE in Figure 12), and values calculated for the erosion analysis (called TWL in Figure 11). The comparison is an indication of methodology uncertainty because the two sets (BFE vs. TWL) of estimates entail different data and methods. The values compare reasonably well, with the TWL typically lower by an average of 4 feet. This may be a result of the use of

GCM rather than real data, and indicates that the TWL estimates used to force future erosion may be systematically low. This implies that erosion estimates are also biased low since higher TWL would increase erosion, although the relative change methods used in this study are probably less susceptible to accuracy bias. There is a greater deviation between BFE and TWL for lower TWL values, indicating perhaps a bias in the wave transformation calculations that over-predict refraction shadows. This systematic error would tend to under-predict erosion and flooding estimates in sheltered areas and potentially over-predict rates at exposed areas. It is important to note however that none of these data are completely accurate. The published values are generally based on studies completed around 20 years ago with very sparse resolution. It should also be noted that this is the first time coastal flood estimates have been completed for the California coast, and hence it is very difficult to assess their accuracy within the budget and schedule constraints of this study.

Overall, in simple terms, California can expect to lose several hundred feet of shore along the entire coast over the next 100 years. While the actual amount of erosion at particular locations may vary substantially from this average, order of magnitude estimate, the point is that most oceanfront development, be it public or private, is at increasing risk.

While the exact timing of these erosion extents is uncertain, the potential erosion mapped during this project is likely to occur at some point in the future. Even if greenhouse gas emissions were to be stopped today, sea levels are expected to rise for centuries given the time scales associated with climate processes and feedbacks (IPCC 2007). This sea level rise will lead to an acceleration of erosion. Management responses to increasing coastal hazards will determine the future economic and ecological value of the coast of California. The spatial representation of coastal hazards is an important step in evaluating levels of risk, developing adaptation strategies and educating people.

This study utilized the best available data sets at the statewide scale. However the limitations of each input data set and the resulting outputs from this study highlight the need for further research, new data set collection, and long term monitoring. The methodology applied in this project evolved from recent research and shows some promise for evaluating potential erosion for management applications regarding coastal hazards. This methodology was purposely designed to be updateable using improved data sets and modular to facilitate application of improved predictive erosion models. However, without higher resolution statewide data sets, further statewide analysis is probably unnecessary. It is recommended that more focused local pilot studies be funded to refine the predictions and methodology (see section 6 Future work).

5. LIMITATIONS ON ACCURACY

The purpose of this study was to provide an estimate of ***potential*** future erosion NOT to predict actual erosion.

5.1 EXISTING DATA SETS

Appropriate available data were selected based on the scale of the study area. There are large gaps and inherent variability and uncertainty with each input data sets, which affect the results transmitted herein.

5.2 1998 LIDAR

The most comprehensive regional topographic data set was captured at the end of the last major El Niño event. This data set, while spatially comprehensive, represents a single point in time at which the coast was significantly eroded. A review shows areas of eroded conditions characterized by low toe elevations and narrow beaches, as well as other areas which accreted, probably due to deposition of material following flood events, eroded dunes and cliffs. This data set was used in both the USGS shoreline change studies and for the topographic analysis in this study. It has introduced unknown levels of uncertainty into this project. It is also unlikely that this data set is representative of existing conditions in 2008. Consequently, a more "typical" LIDAR data set may be more useful for future analysis.

5.3 EROSION RATES

The hazard zones are derived using future erosion rates derived partly from historic erosion rates. The historic erosion rates were estimated by others and not independently checked or evaluated by PWA. In particular,

- The historic rates are long-term average values, which may not represent existing erosion rates.
- The last shoreline used to generate these erosion rates was the 1998 LIDAR data (see discussion above).
- There are "gaps" in the available data. These gaps were filled by using published rates from nearby locations with the same basic geologic classification.
- The rates for sandy shores sometimes indicated accretion rather than erosion.
- For simplicity shoreline erosion rates were used for all sandy shores and cliff erosion rates were used for all cliff / cliff backed shores.

5.4 BACKSHORE CLASSIFICATION

The backshore was characterized as sandy (dunes) or erosion-resistant cliffs. The classification as dune or cliff is not entirely adequate for the complex coastal geology and geomorphology.

- In some locations, the shoreline geology changes as erosion (or accretion) occurs. This is particularly apparent at river mouths with sand spits fronting cliffs, or in cliffs with multiple geologic units, for example.
- Some cliffs consist of ancient sand dunes and weekly consolidated sedimentary deposits that can erode as rapidly as sand dunes.
- The scale of the geology and the scale of the backshore classification are different than the block scale at with these calculations were applied.
- Some shoreline reaches are armored (seawalls, rock revetments, etc.), which would reduce the actual erosion behind the armoring as long as the armoring is intact. Armoring was not considered in the erosion analysis.

5.5 GLOBAL CLIMATE MODEL

The erosion estimates respond to water level and wave time series output from a Global Climate Model (GCM) and are provided by others. PWA checked basic parameters such as tide range and overall sea level rise which agreed well with existing tide data and climate change scenarios prescribed for the study. Possible limitations are as follows:

- One GCM run was used, not an ensemble of multiple runs.
- One wave time series was used for all climate change scenarios, since the GCM did not indicate major changes to the wave statistics with climate change. Other GCM runs have shown some differences as have other researchers.
- Water level and wave time series were derived for three locations to approximate regional differences, primarily associated with latitude each of three regions (Pt Conception, San Francisco and Crescent City).
- Only GCM output data were used in order to preserve the implicit coincidence of high water level and waves, and in order to develop an estimate of relative changes. Existing conditions were based on the first ten years of model output, rather than real data that is more coincidental with the time periods that historic rates were calculated.

5.6 WAVES

- Wave refraction transformations were accomplished only to the 10 meter contour, and do not include wave transformation processes (refraction, breaking, etc.) in the surf zone that affect the actual wave run-up elevation on the shore.

- Wave transformations were detailed (using directional spectra) but were condensed to single spectral parameters for runup analysis (wave height and wave period).

- Only winter wave run-up values were provided by Scripps and used to calculate the percent exceedance, not an entire annual time series.

5.7 THE TOTAL WATER LEVEL (TWL)

Calculations were made with an empirical equation for wave run-up developed for beaches (Stockdon *et al.* 2006). This equation was selected partly for its ease of application.

- The equation is applied to conditions beyond the bounds of the empirical data used to develop it, especially for very steep slopes, cliffs and armored shores.

- Wave setup is addressed by the equation, but the effect of wave groups on dynamic setup could be addressed better using other more complex methods.

5.8 100 YEAR STORM EVENT

PWA estimated the 100-yr return period (annual exceedance probability of 0.01) TWL for use in establishing the erosion hazard zone of sandy shores. A review of available flood studies accomplished for FEMA indicated that the 100-year coastal flood level has not been previously calculated for most of the California coast. Hence, PWA estimated it as the 100-year TWL based on the GCM output and the run-up estimates conducted by PWA.

5.9 FUTURE EROSION

Future erosion was estimated using a simple conceptual model which included simplified geometric response models for sandy dune and cliff-backed shores. Available data do not allow confirmation of the model. In fact there is debate in the literature whether it is possible to estimate the erosion of rocky cliffs in many cases because of the inherent complexity of the processes and conditions affecting those processes.

- The method is based upon recent research which indicates coastal erosion is related to the percent time and intensity by which wave runup exceeds the elevation of the toe of the dunes and cliffs.

- The methods used in this study address wave action and, to a limited extent, material properties, but neglect terrestrial processes which may change with climate change.

- A linear increase in historic erosion with increased TWL is assumed.

- The potential future erosion is provided, rather than the actual, which may lag the climate change for very hard shores.
- Planform impacts on shoreline evolution were not considered.
- Sediment budget effects on shoreline evolution were not considered. In particular, the effect of dune and cliff erosion to mitigate the rate of erosion by providing littoral material was not included.
- The angle of repose was assumed to be constant at 32° for all dune face slopes while in reality this is likely less steep of a slope due to vegetation and mixed sediment size gradations.

These limitations highlight the need for future research, additional data collection, and long term monitoring.

6. FUTURE WORK

The accuracy of the projections presented here could be improved by carrying out the following:

- Detailed monitoring and data collection program including seasonal fluctuations of sand levels, beach slopes, and elevations of the toe.
- Validate erosion models using hindcast data, observed (not modeled) TWL, and historic shoreline changes. Apply range of erosion models to assess method uncertainty and sensitively of results.
- Focused regional or local studies that include improved input data and more refined analyses, including considerations of sediment transport and supply, and shoreline evolution.
- Evaluation of alternative cliff erosion methods, including a more detailed formulation of geology and use of real data.
- Field data collection to measure erosion and parameters affecting erosion such as rock hardness, angles of stability, and groundwater influences. This will require a long-term monitoring effort at a range of locations.
- Further application of the CDIP MOP sites analysis to provide estimates of near-shore wave conditions and littoral responses.
- Application to a range of scenarios.
- Improved 100-year TWL estimates.
- Evaluation of various management approaches to address the erosion and flood hazards posed by climate change.
- New LIDAR flights capturing non-storm conditions, preferably spring and fall.
- Updated erosion estimates based on more recent topography (LIDAR).
- More detailed evaluation of profile parameters for each location, using other data sets such as new LIDAR.

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10. FIGURES

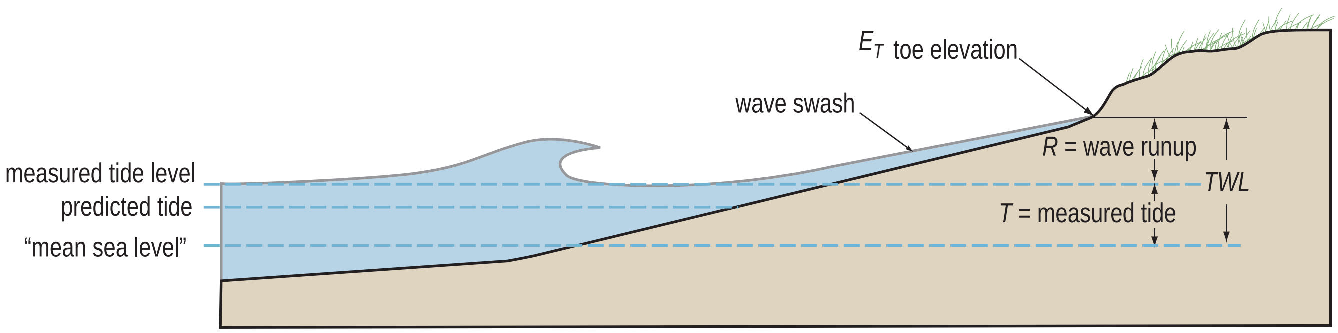

figure 1

OPC Sea Level Rise Assessment

Total Water Level Definitions

PWA Ref# 1939

PWA

1939.00

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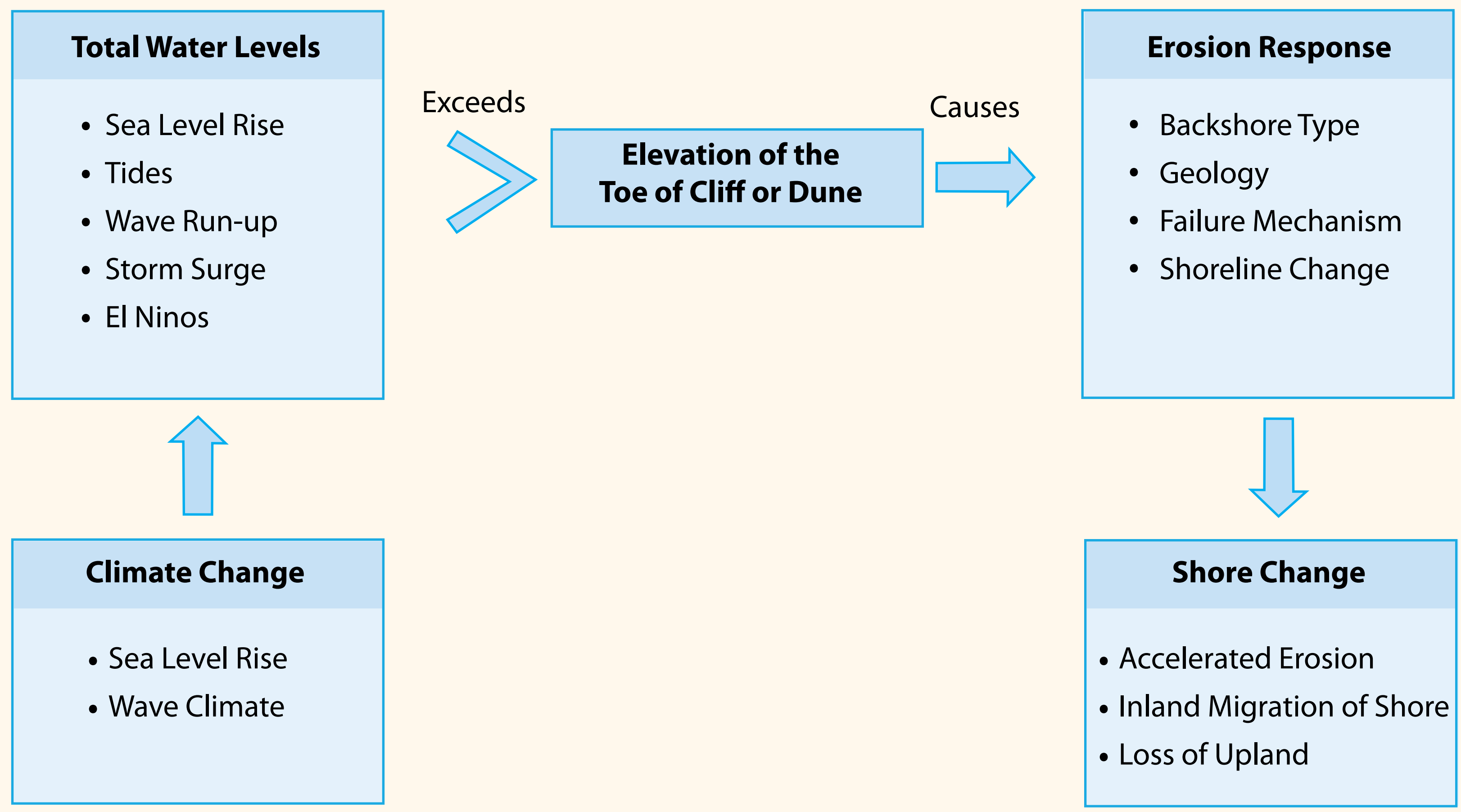

figure 2
OPC Sea Level Rise Assessment

Generalized Methodology

PWA Ref# 1939

PWA

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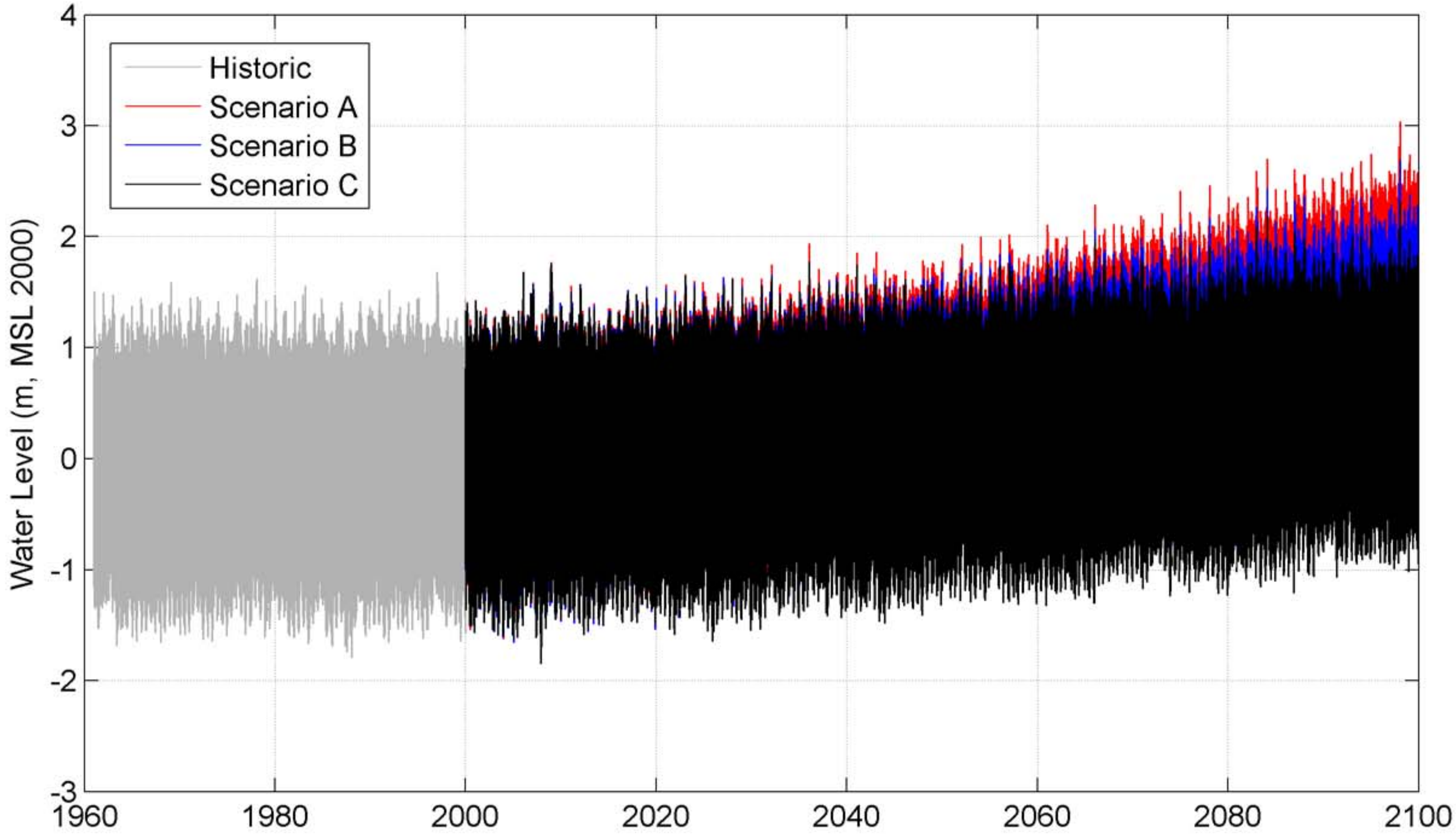

figure 3

OPC Sea Level Rise Assessment

Simulated Water Level - San Francisco

PWA Ref# 1939

PWA

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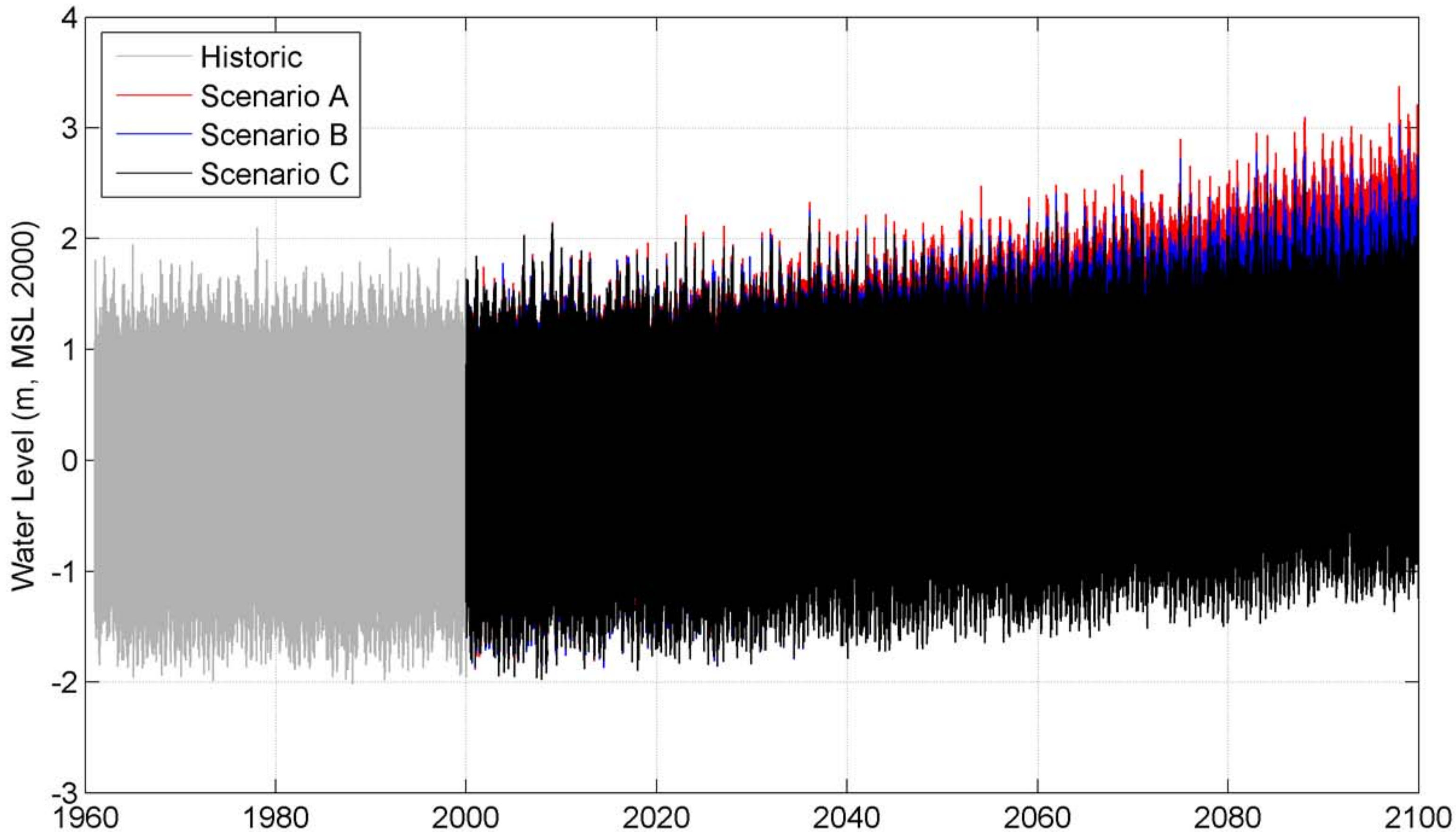

figure 4

OPC Sea Level Rise Assessment

Simulated Water Level - Crescent City

PWA Ref# 1939

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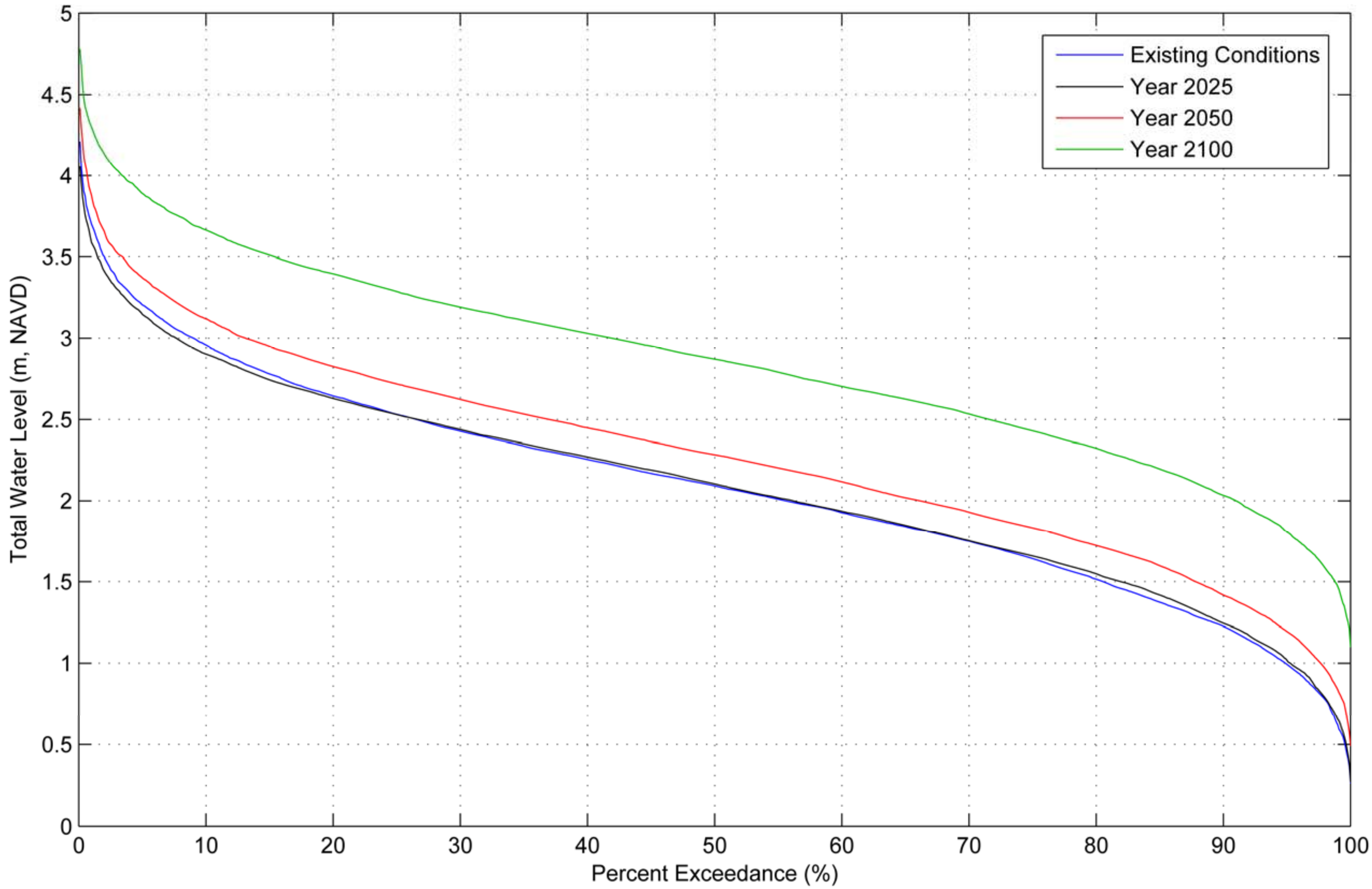


Source: UCSD wave climate and sea level data for 2001-2100 for MOPS Station #SL345 (Morro Rock). Runup elevations calculated from Stockdon (2006). Total water level is the sum of still water level (SWL) + wave setup + wave runup. Beach slope = 1:5.

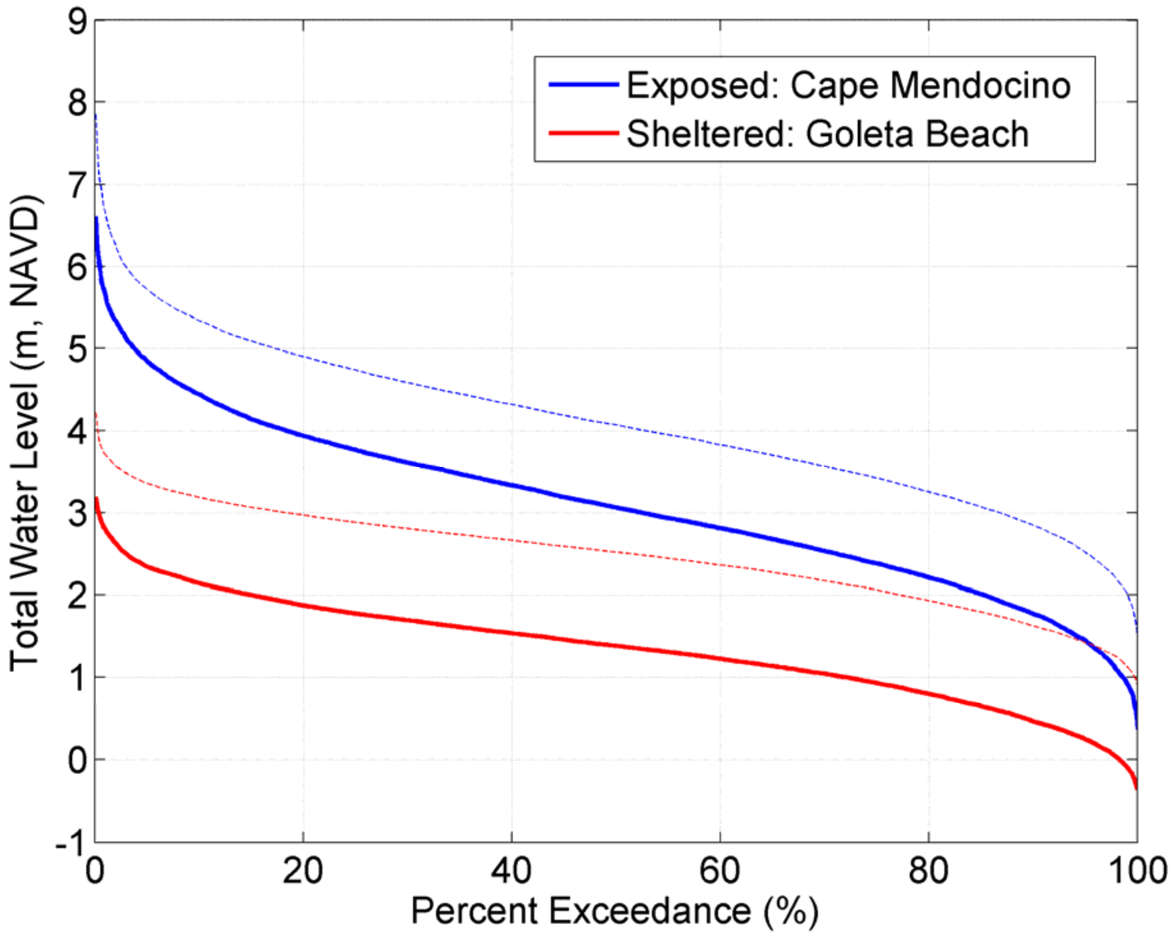
figure 5

OPC Sea Level Rise Assessment

Example of Total Water Level Exceedance Curves for Transect: 1743 (Jalama Beach)

PWA Ref# 1939

PWA



Source: UCSD wave climate and sea level data for 2001-2100. Runup elevations calculated from Stockdon (2006). Total water level is the sum of still water level (SWL) + wave setup + wave runup.

Notes: Average percent exceedance curves for 2001-2010 (solid) and 2090-2100 (dashed) at Cape Mendocino and Goleta Beach.

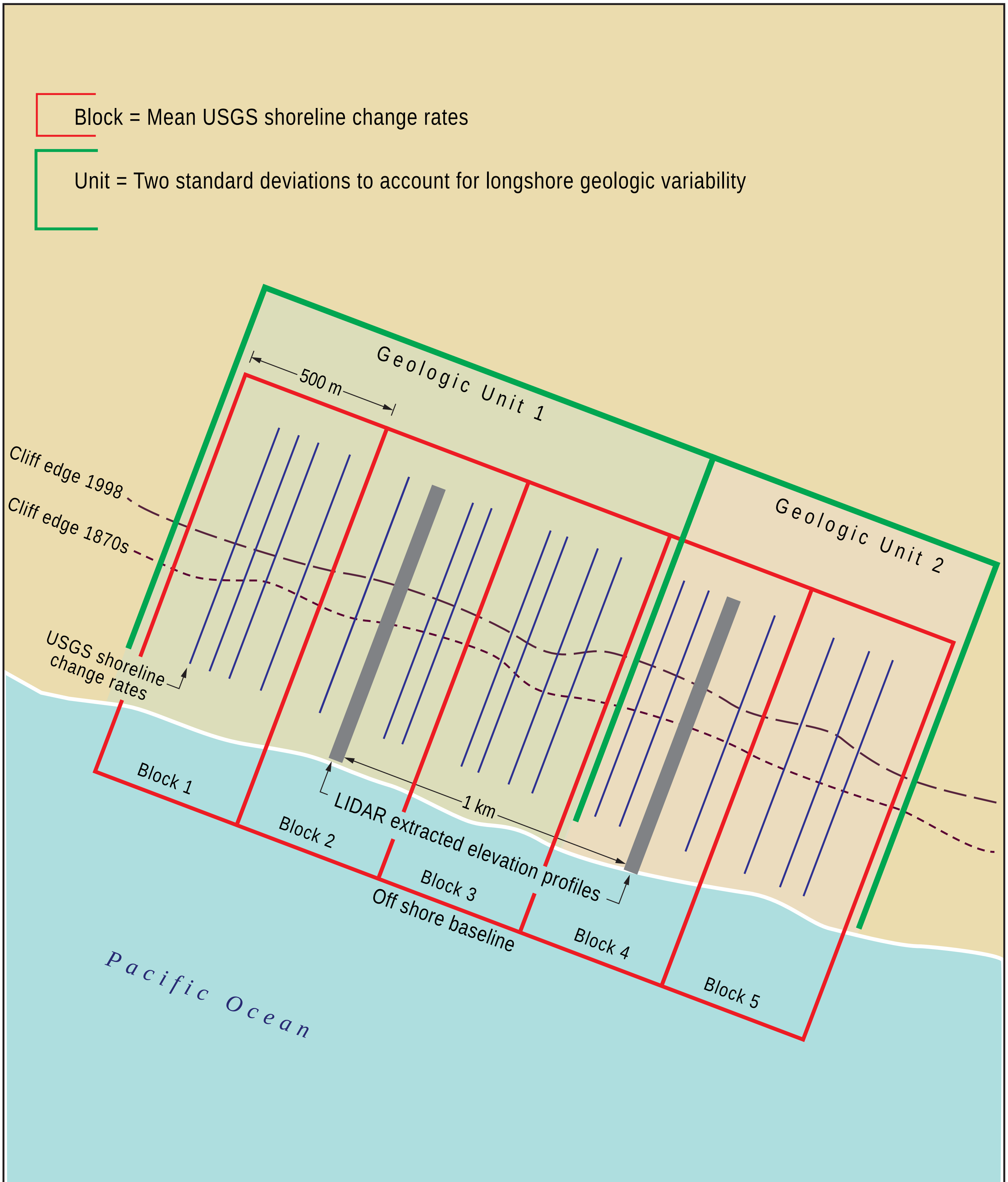
figure ***6***

OPC Sea Level Rise Assessment

Example Total Water Levels for Exposed and Sheltered Coasts

PWA Ref# 1939

PWA



Notes: The historic erosion rates from the USGS were derived at 50m spacing for sand beaches, and 20m spacing for cliff-backed shorelines. The transects being used for this study were averaged in blocks based on similarity of geologic unit and proximity to PWA transects. Each continuous geologic unit was subdivided into 500m blocks. The analyses were conducted at this block scale.

figure 7
OPC Sea Level Rise Assessment

Method Of Backshore Classification

PWA Ref# 1939

PWA

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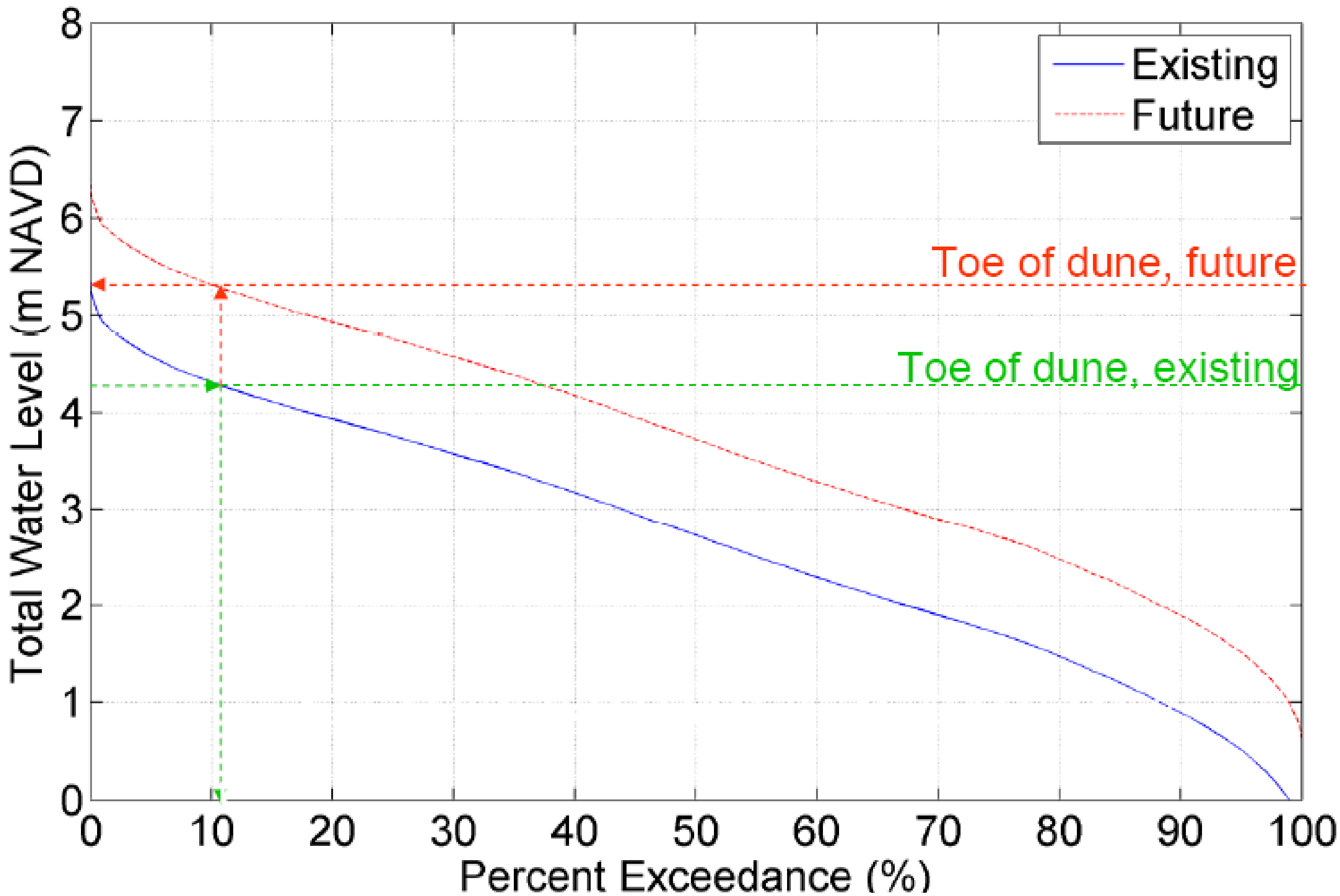

figure ***8***

OPC Sea Level Rise Assessment

Dune Methodology Schematic

PWA Ref# 1939

PWA

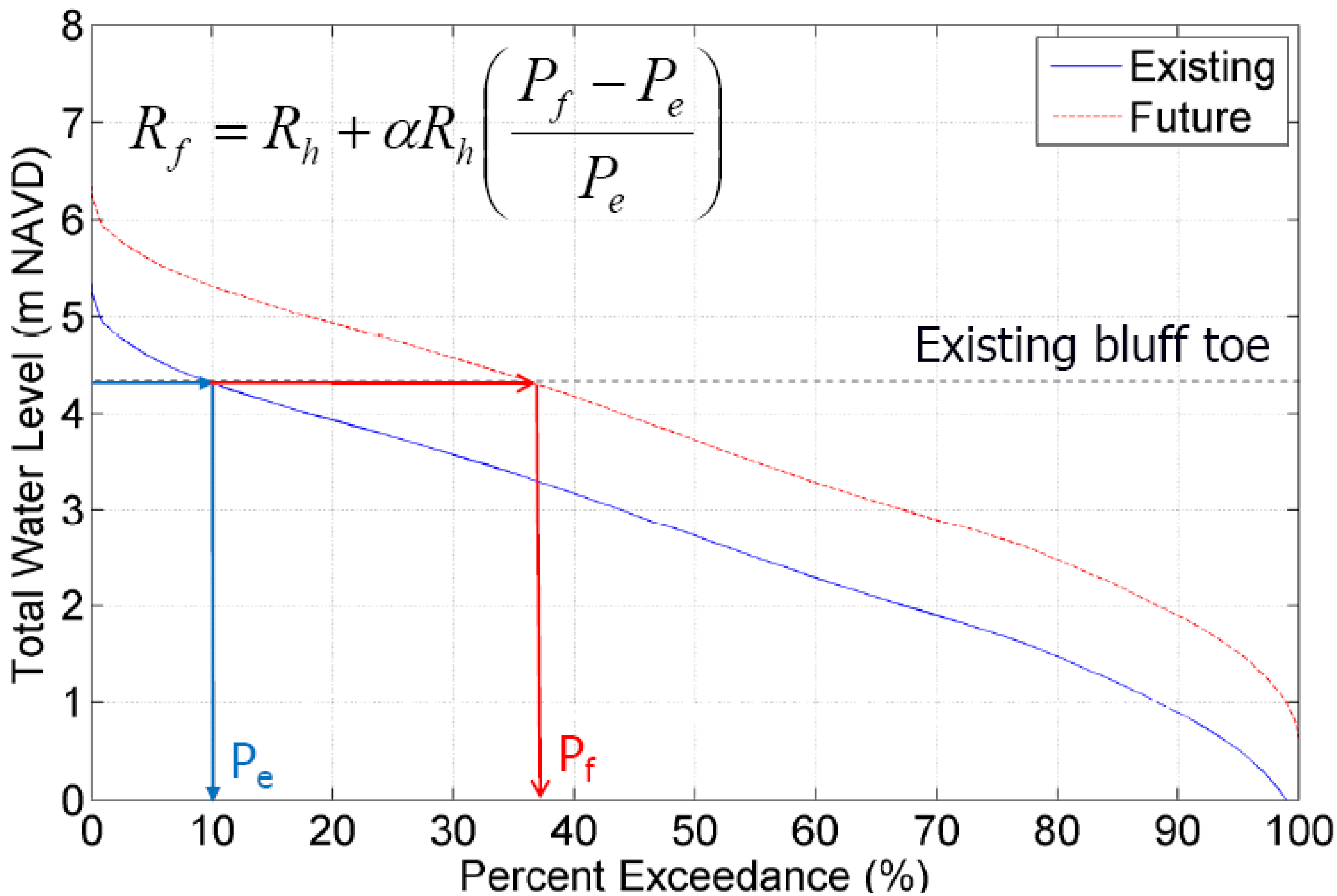

figure **9**
OPC Sea Level Rise Assessment

Cliff Methodology Schematic

PWA Ref# 1939

PWA

Dune Hazard Zone (DHZ) = climate change (sea level rise & wave climate) + historic erosion + 100 year storm erosion

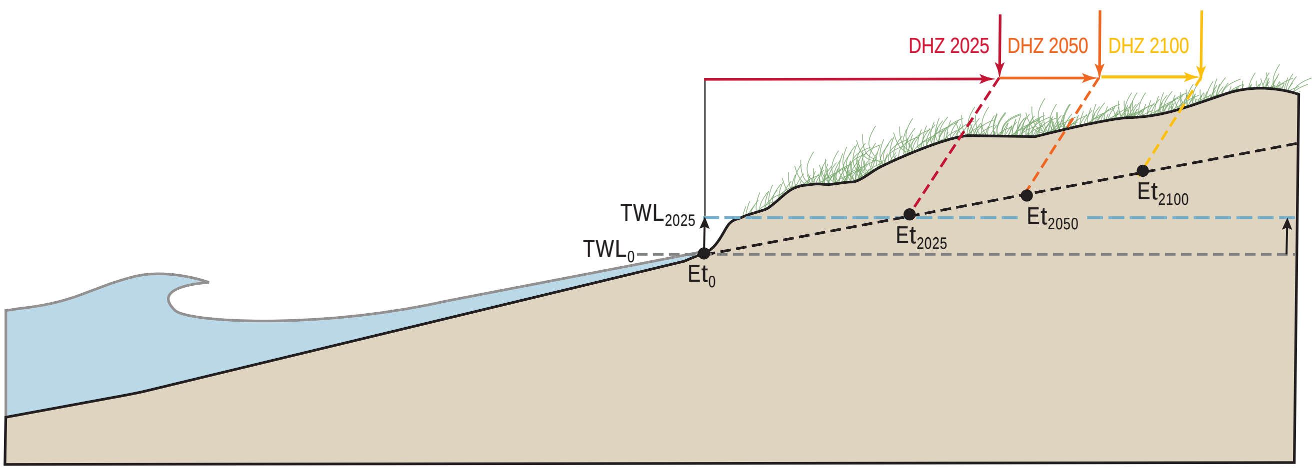

figure *10-A*

OPC Sea Level Rise Assessment

Example Results for Dunes - Cross Section

PWA Ref# 1939

PWA

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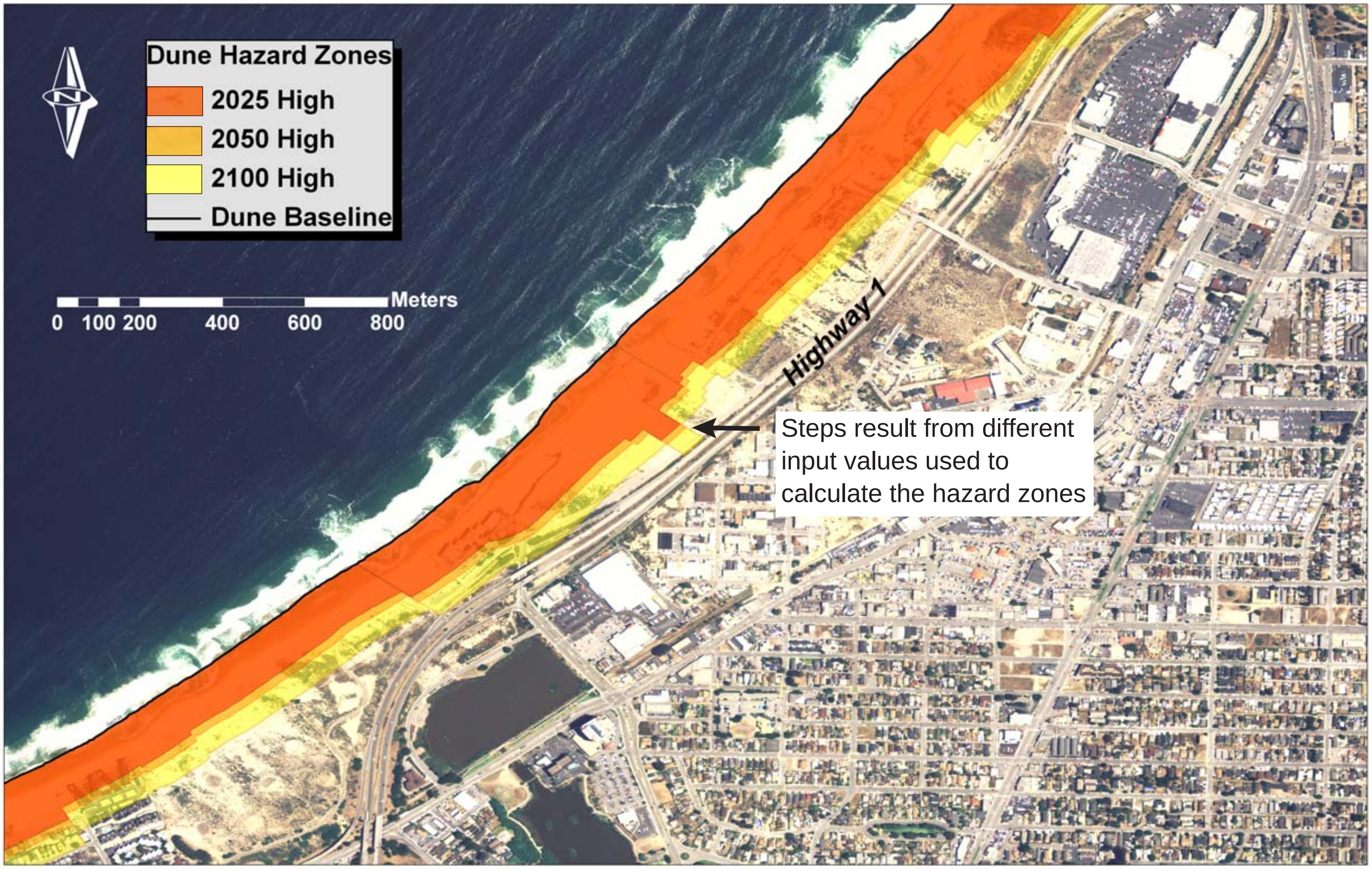

figure 10-B
OPC Sea Level Rise Assessment

Example Results for Dunes - Map View

PWA Ref# 1939

PWA

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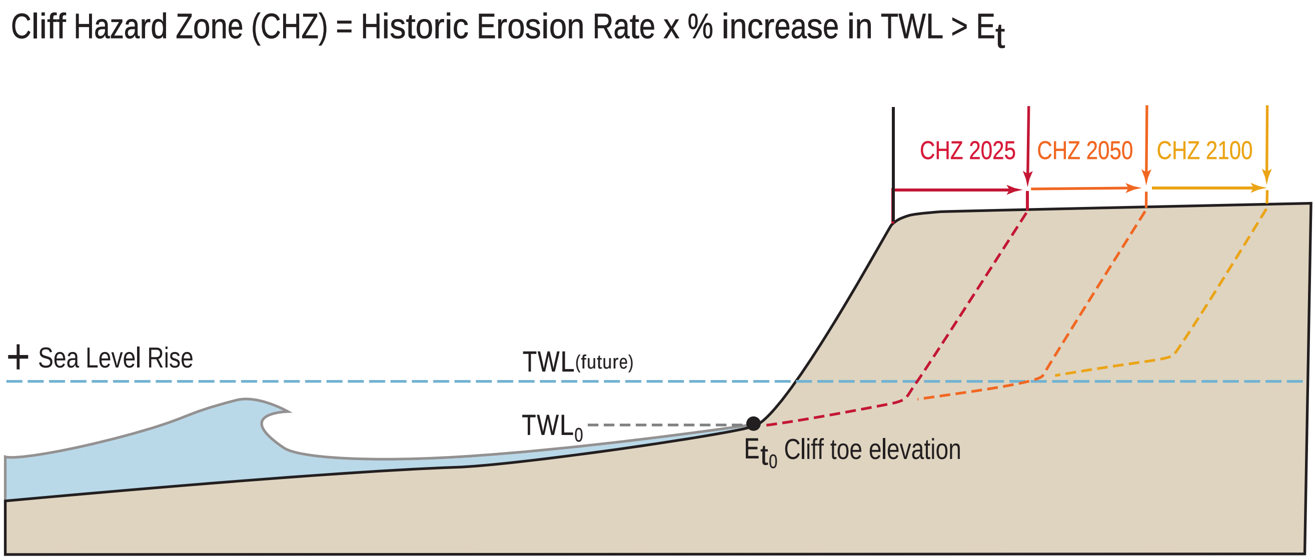

figure 11-A

OPC Sea Level Rise Assessment

Example Results for Cliffs - Cross Section

PWA Ref# 1939

PWA

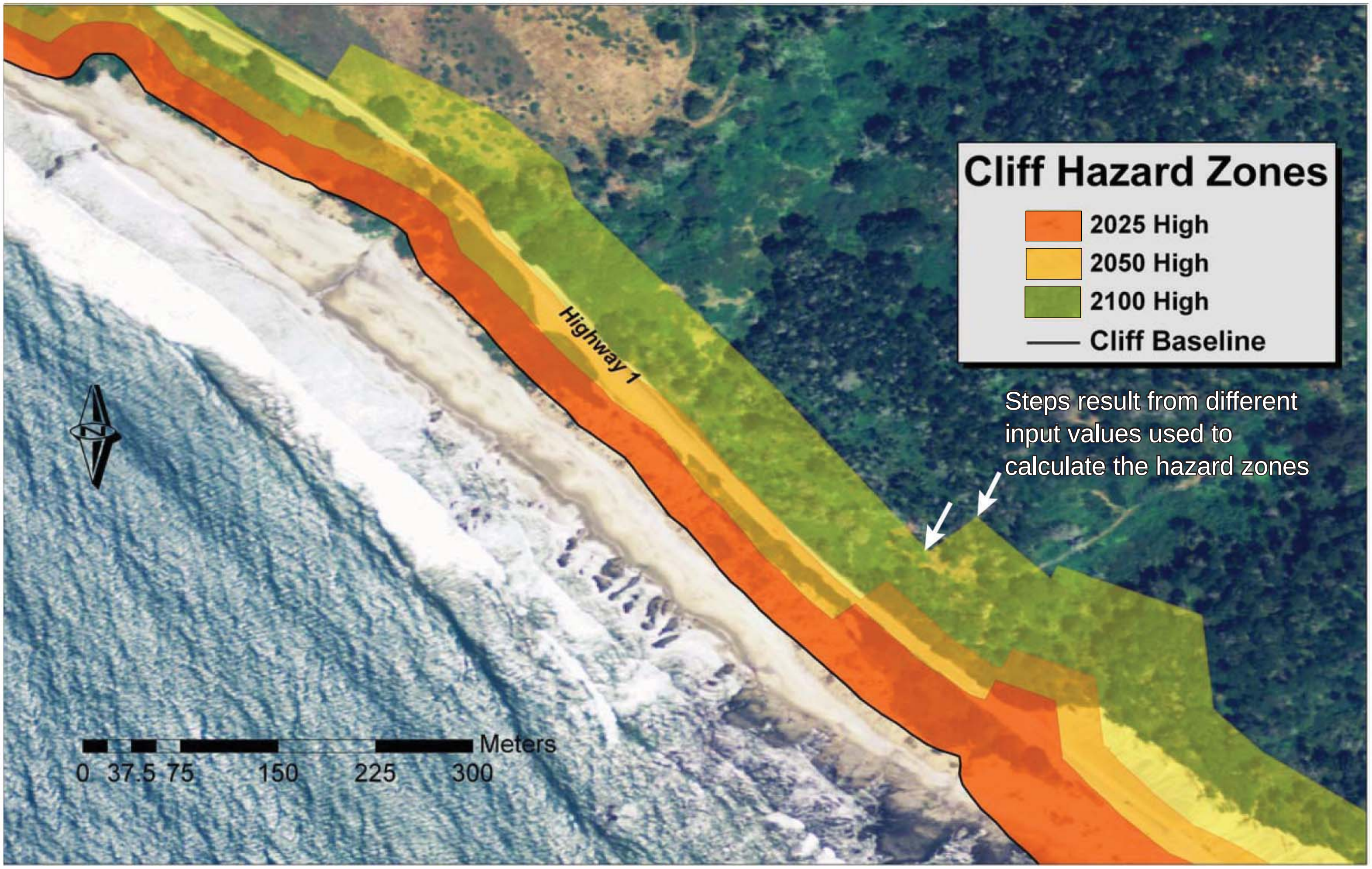

figure *11-B*
OPC Sea Level Rise Assessment

Example Results for Cliffs - Map View

PWA Ref# 1939

PWA

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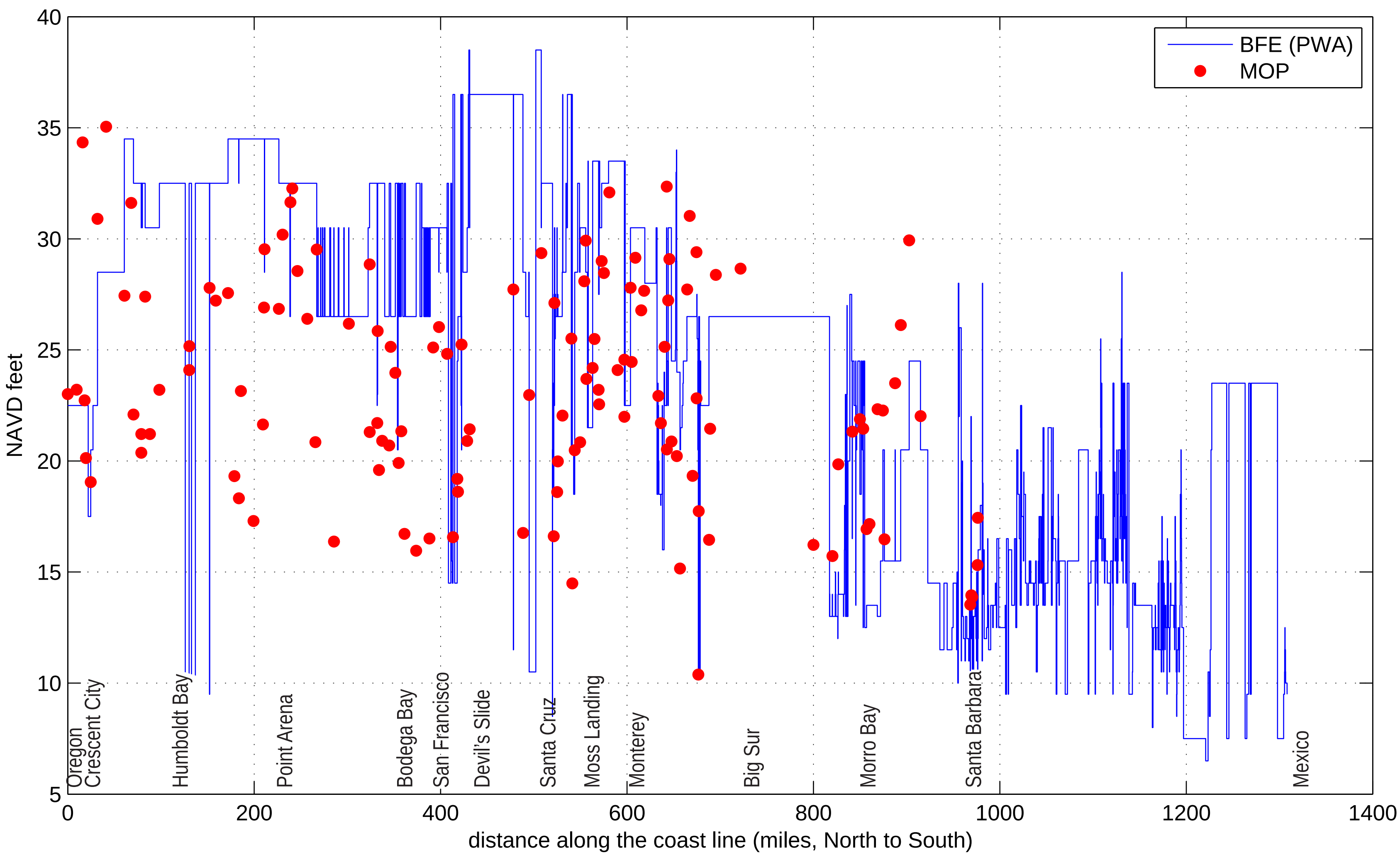

Source: Base Flood Elevations (BFE) are based on the 100-yr flood elevations published by FEMA. MOP flood elevations are estimated as the maximum of the 100-yr time series of total water level at each MOP site.

figure 12

OPC Sea Level Rise Assessment

Estimated Coast Flood Elevations

PWA Ref# 1939

PWA

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Appendix 1- List of Figures and Tables

Figures and Tables that provide additional information about the available input, intermediate and output data follow this page in the order listed below.

General

Dunes

Cliffs

CDIP Monitoring and Prediction (MOP) Description and References

http://cdip.ucsd.edu/documents/index/product_docs/mops/mop_intro.html

Tidal Datums for UCSD 1961-1999 sea level simulation, San Francisco

	Model		NOAA		
	m MSL	m NAVD	(m, NAVD)	Diff (cm)	Diff (in)
MHHW	0.815	1.784	1.8	-1.64	-0.65
MHW	0.654	1.623	1.61	1.29	0.51
MSL	0.000	0.969	0.99	-2.1	-0.83
MTL	-0.002	0.967	0.97	-0.26	-0.10
MLW	-0.657	0.312	0.36	-4.81	-1.89
MLLW	-0.956	0.013	0.02	-0.72	-0.28

Diurnal Range		
Model	NOAA	
1.77	1.78	m
5.81	5.84	ft

Tidal Datums for UCSD 1961-1999 sea level simulation, Crescent City

	Model		NOAA		
	m MSL	m NAVD	(m, NAVD)	Diff (cm)	Diff (in)
MHHW	0.960	1.974	1.979	-0.48	-0.19
MHW	0.774	1.788	1.784	0.37	0.15
MSL	0.000	1.014	1.014	0	0.00
MTL	-0.006	1.009	1.024	-1.55	-0.61
MLW	-0.785	0.229	0.264	-3.47	-1.37
MLLW	-1.132	-0.118	-0.116	-0.18	-0.07

Diurnal Range		
Model	NOAA	
2.09	2.1	m
6.86	6.89	ft

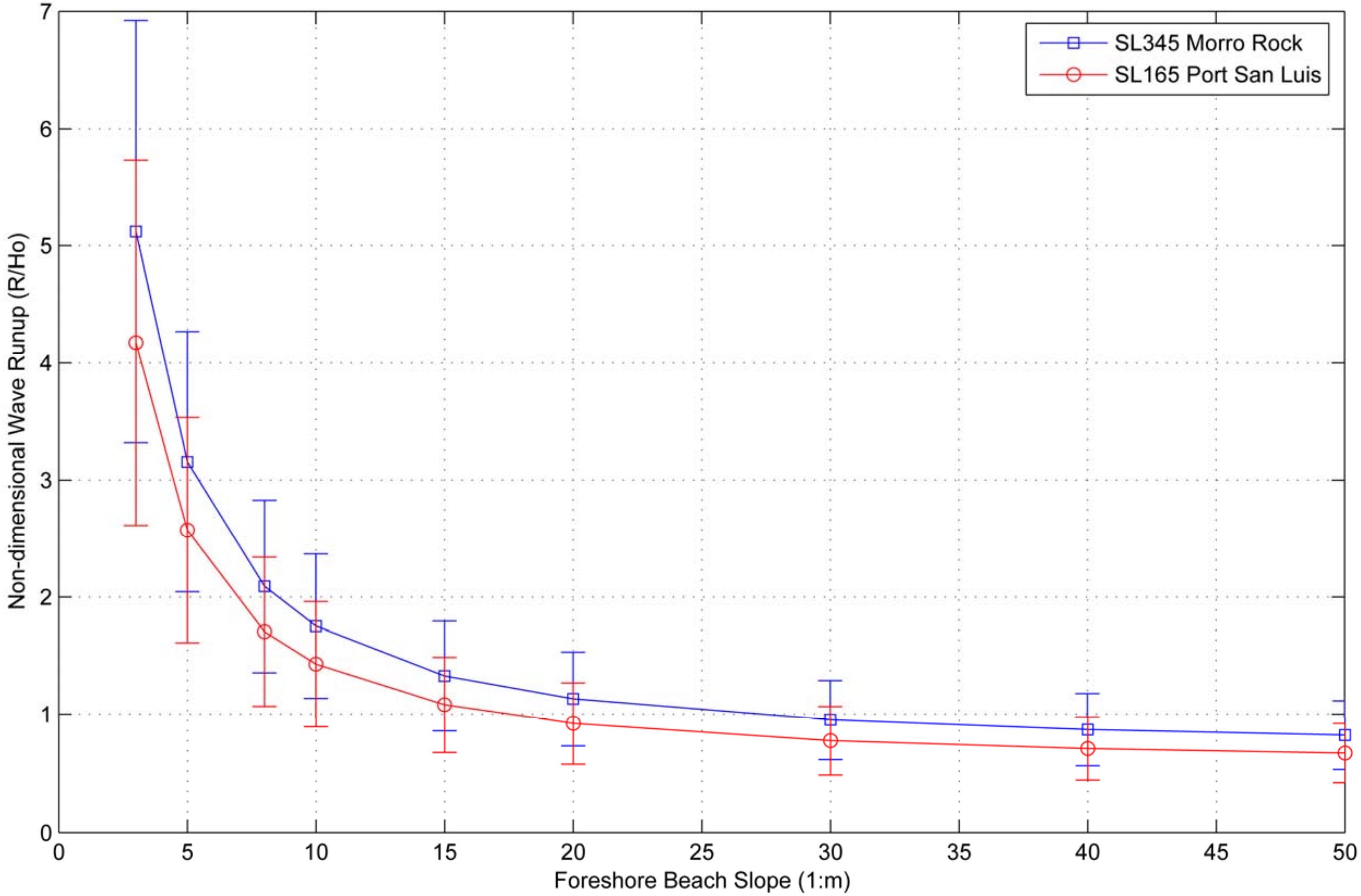
Source: NOAA published tidal datums for San Francisco and Crescent City, CA.

figure 1.1
OPC Sea Level Rise Assessment

Global Climate Model Tidal Datums

PWA Ref# 1939

PWA



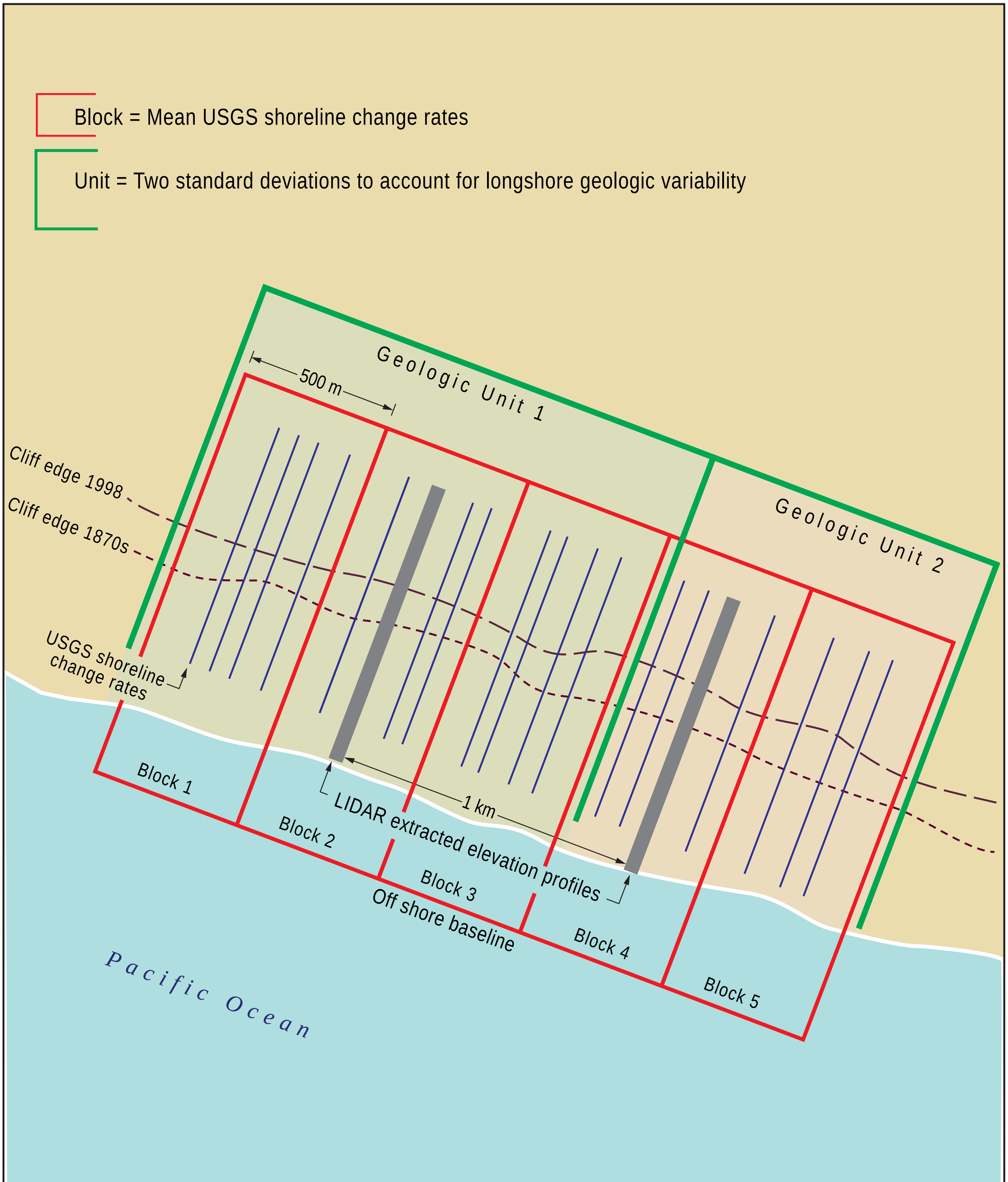
Source: UCSD wave climate data for 2001-2100 for MOPS Station #SL345 (Morro Rock) and #SL165 (Port San Luis Avila Beach).
Runup elevations calculated from Stockdon (2006).
Points indicate mean values +/- one standard deviation.

figure 1.2
OPC Sea Level Rise Assessment

Wave Runup vs. Slope Relationship

PWA Ref# 1939

PWA



Notes: The historic erosion rates from the USGS were derived at 50m spacing for sand beaches, and 20m spacing for cliff-backed shorelines. The transects being used for this study were averaged in blocks based on similarity of geologic unit and proximity to PWA transects. Each continuous geologic unit was subdivided into 500m blocks. The analyses were conducted at this block scale.

figure 1.3

OPC Sea Level Rise Assessment

Block and Geologic Unit Description

PWA Ref# 1939

PWA

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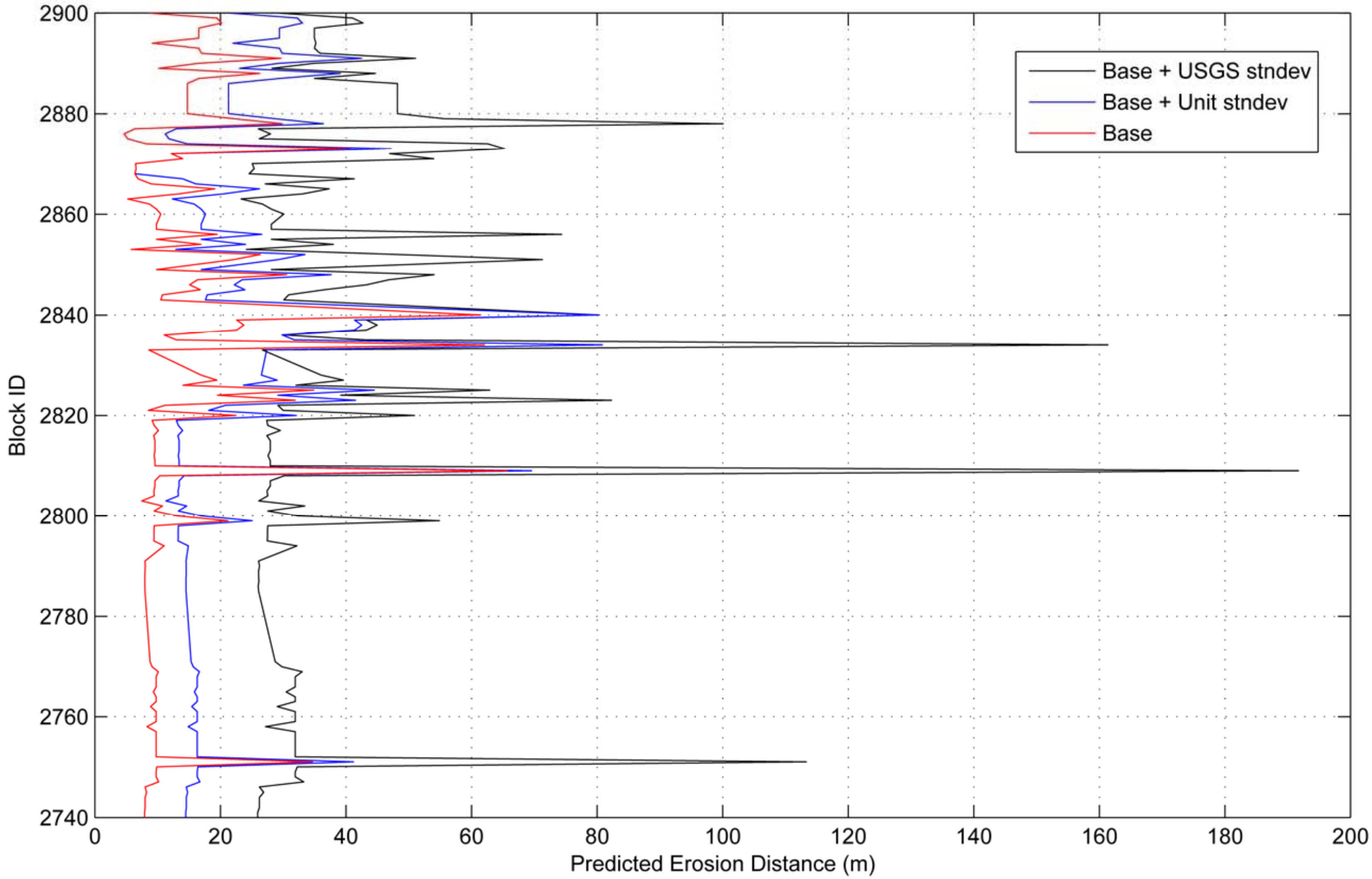

Source: Comparison of three methods to predict future bluff erosion:
(1) Baseline erosion distance,
(2) Baseline erosion + Geologic Unit Stndev, and
(3) Baseline erosion + USGS shoreline change rate error.

For (3), a value of 0.2 m/yr was added to the historic erosion rate (Hapke et al 2006).
This was used to support method of applying two geologic unit standard deviations as a factor of safety.

figure 1.4

OPC Sea Level Rise Assessment

Comparison of factor of Safety Methods for Future Cliff Erosion

PWA Ref# 1939

PWA

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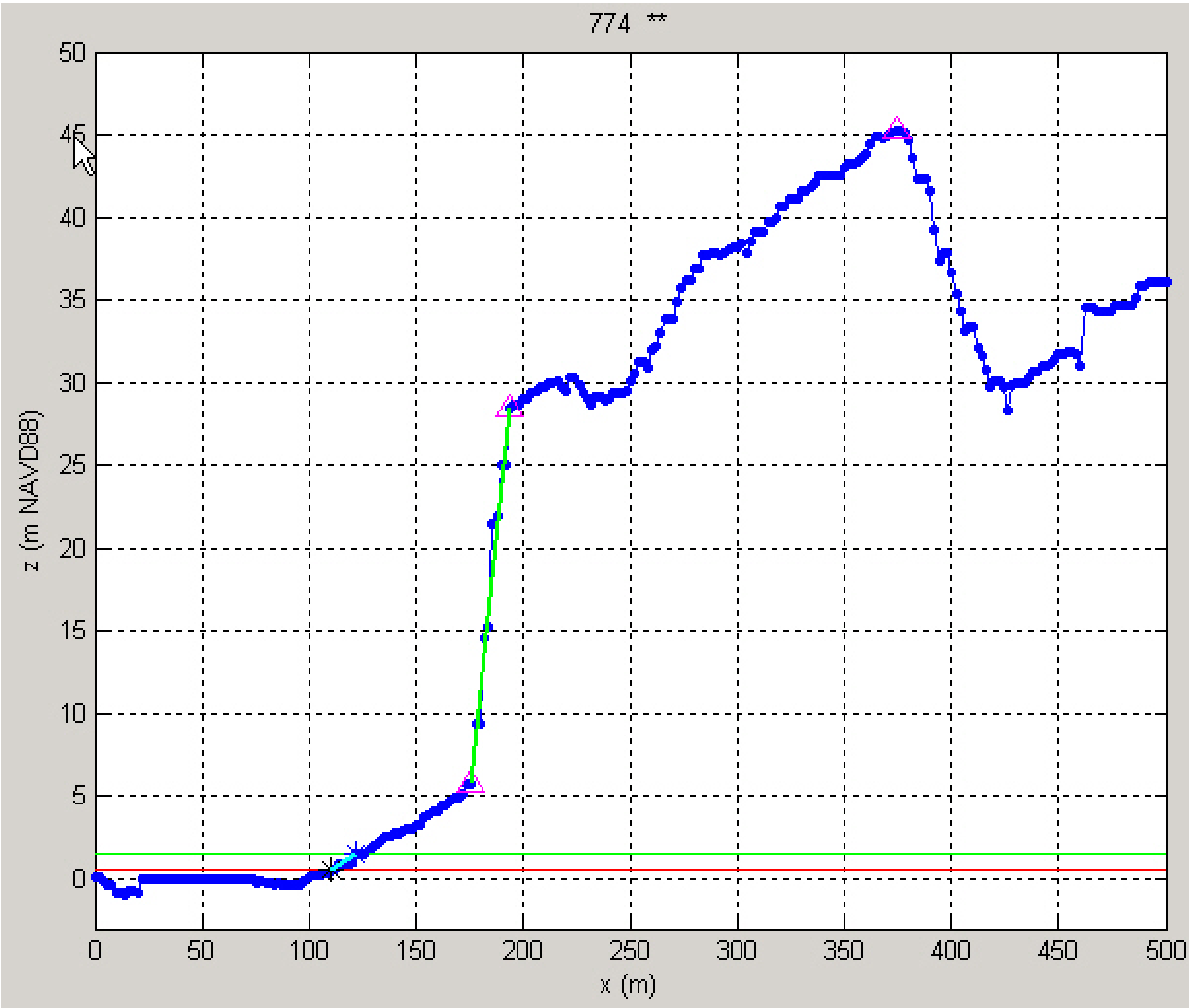


Notes: Sample transect extracted from LiDAR dataset. Horizontal red and green lines bracket elevation range used to determine beach slope. Triangles indicate points selected for cliff toe elevation and top of cliff.

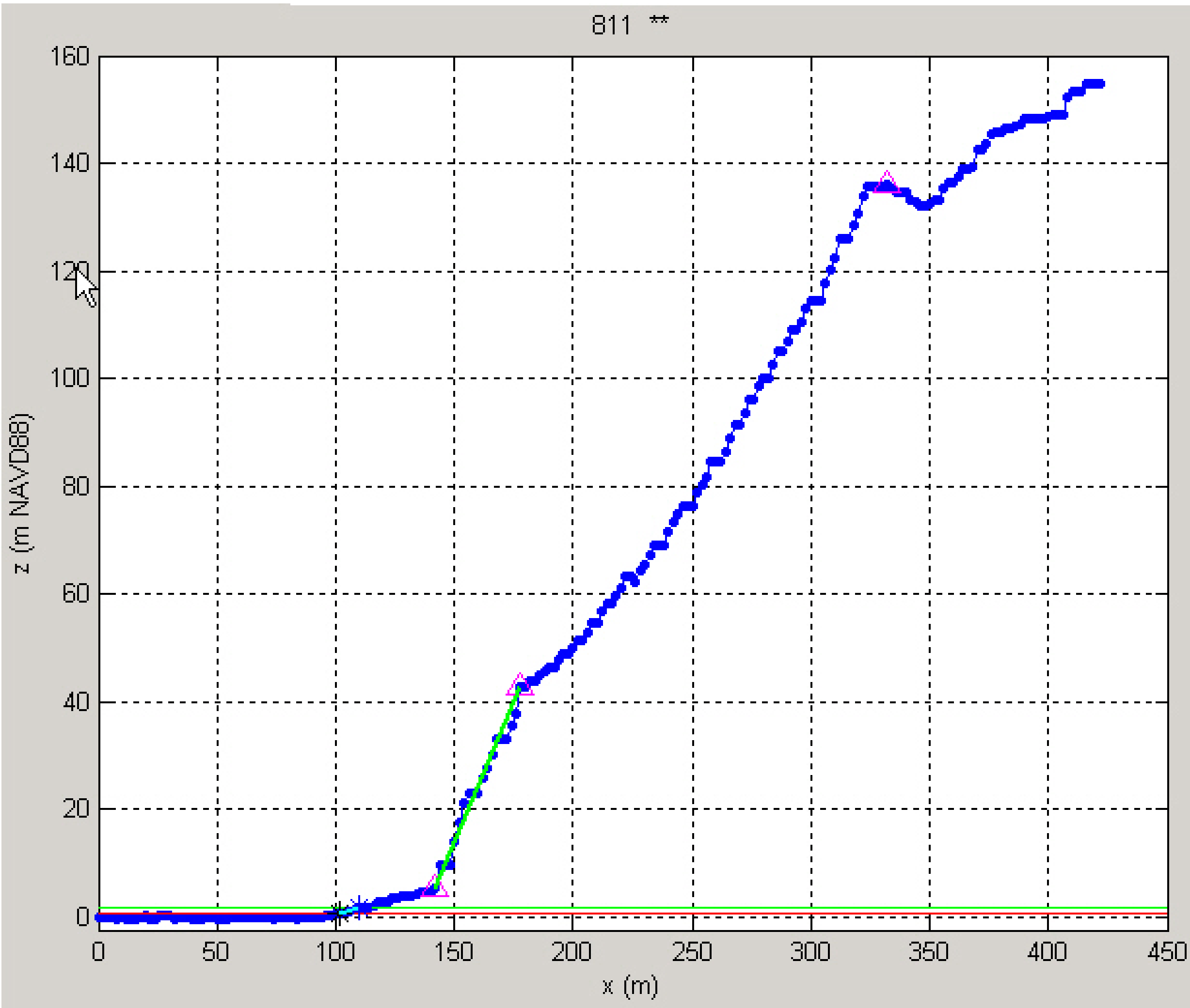
figure 1.5

OPC Sea Level Rise Assessment

Example Cliff Transect from LiDAR

PWA Ref# 1939

PWA



Notes: Sample transect extracted from LiDAR dataset. Horizontal red and green lines bracket elevation range used to determine beach slope. Triangles indicate points selected for cliff toe elevation and top of cliff.

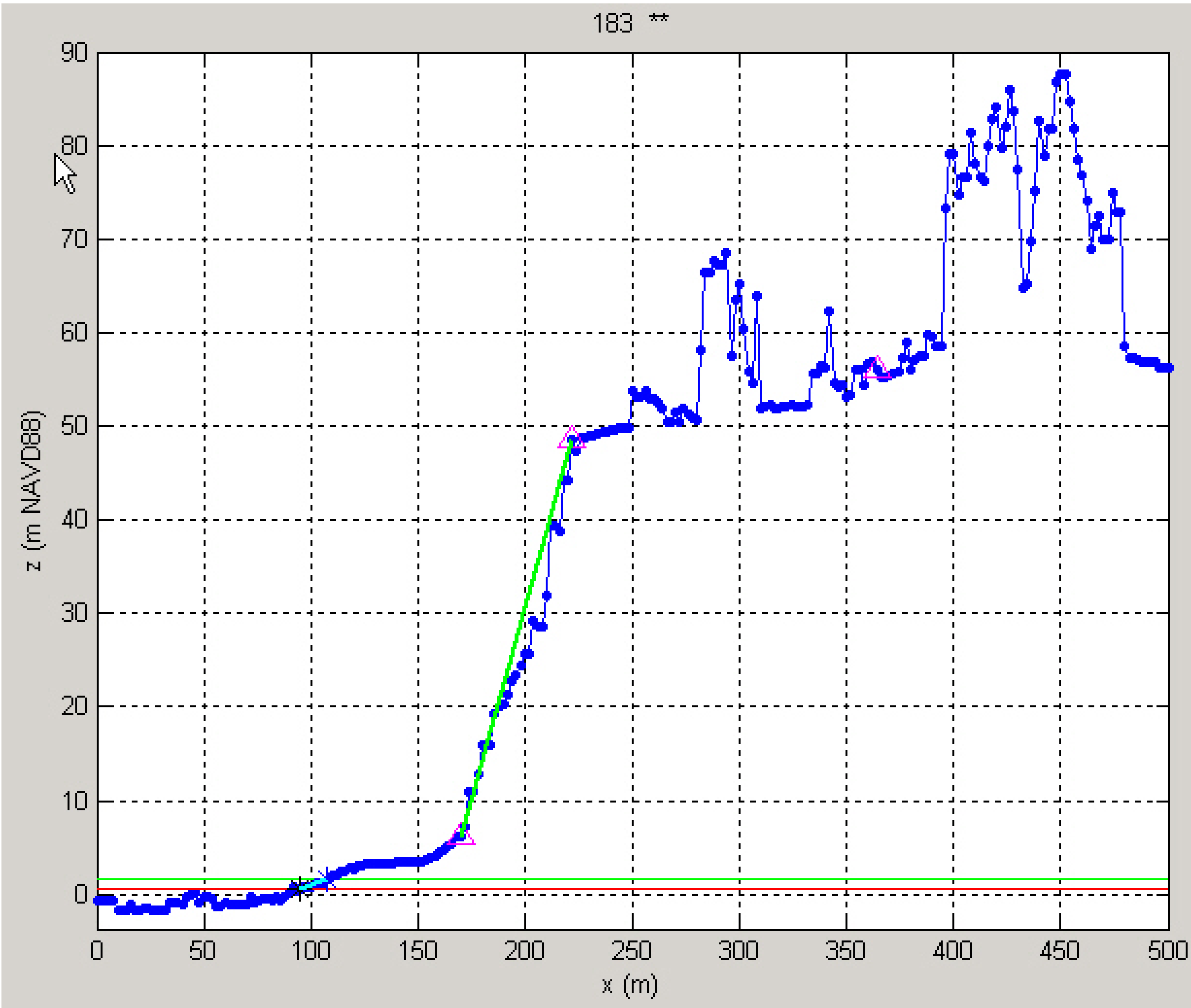
figure 1.6

OPC Sea Level Rise Assessment

Example Cliff Transect from LiDAR

PWA Ref# 1939

PWA



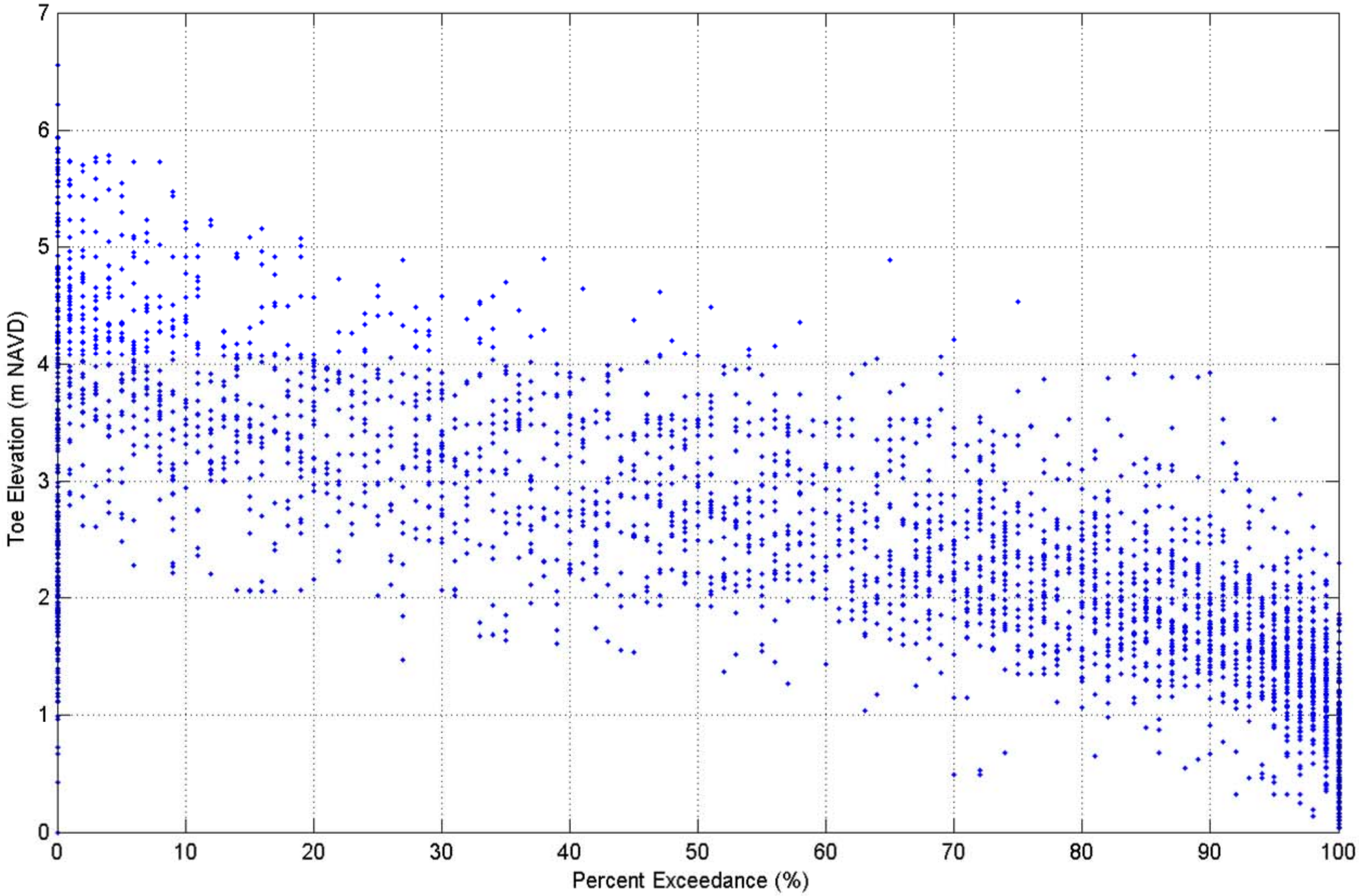
Notes: Sample transect extracted from LiDAR dataset. Horizontal red and green lines bracket elevation range used to determine beach slope. Triangles indicate points selected for cliff toe elevation and top of cliff.

figure 1.7
OPC Sea Level Rise Assessment

Example Cliff Transect from LiDAR

PWA Ref# 1939

PWA



Source: Interpreted toe elevations for dunes and cliffs compared to percent exceedance.

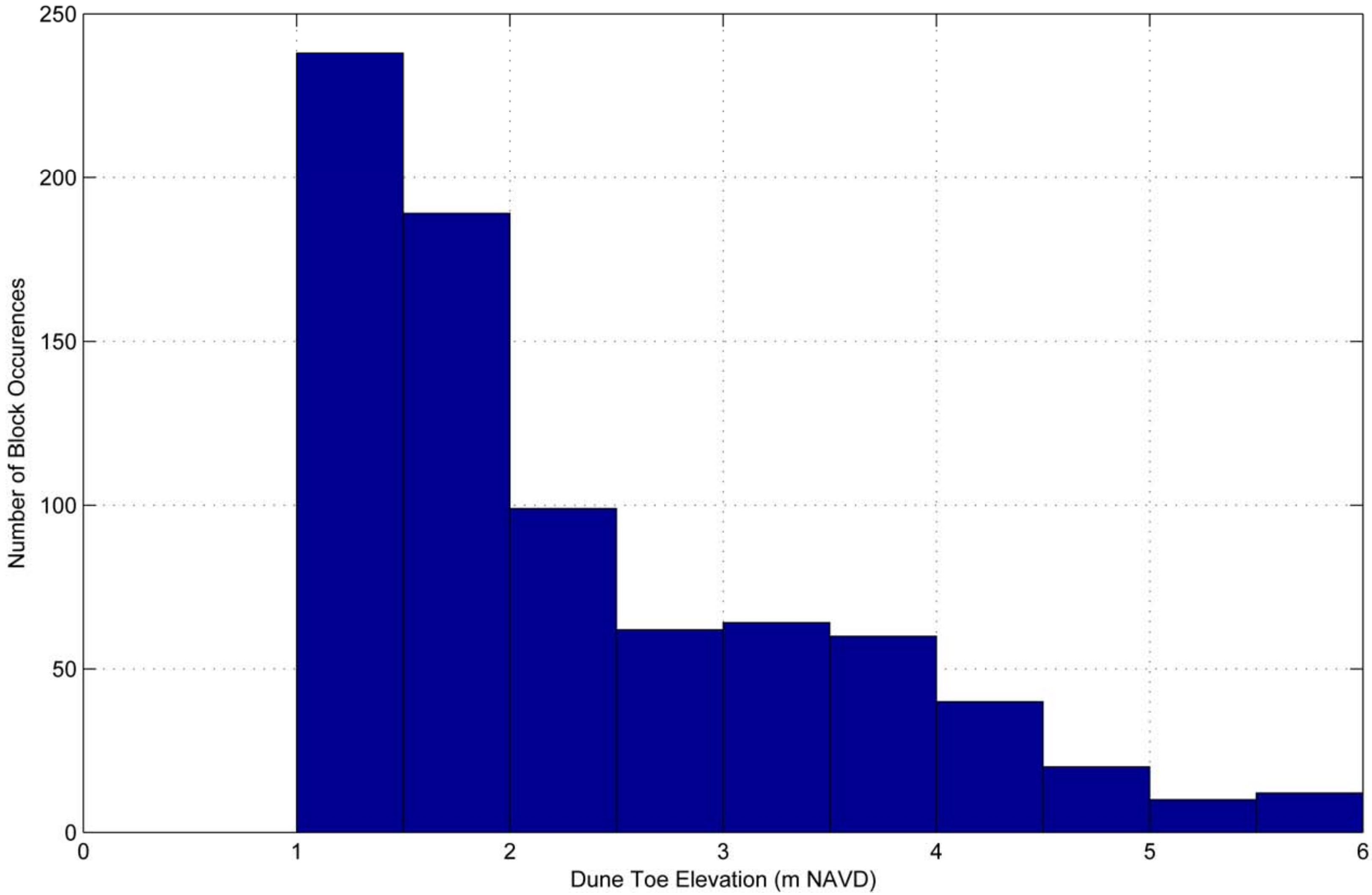
figure 1.8

OPC Sea Level Rise Assessment

Dune / Cliff Toe Elevation
vs. Percent Exceedance

PWA Ref# 1939

PWA

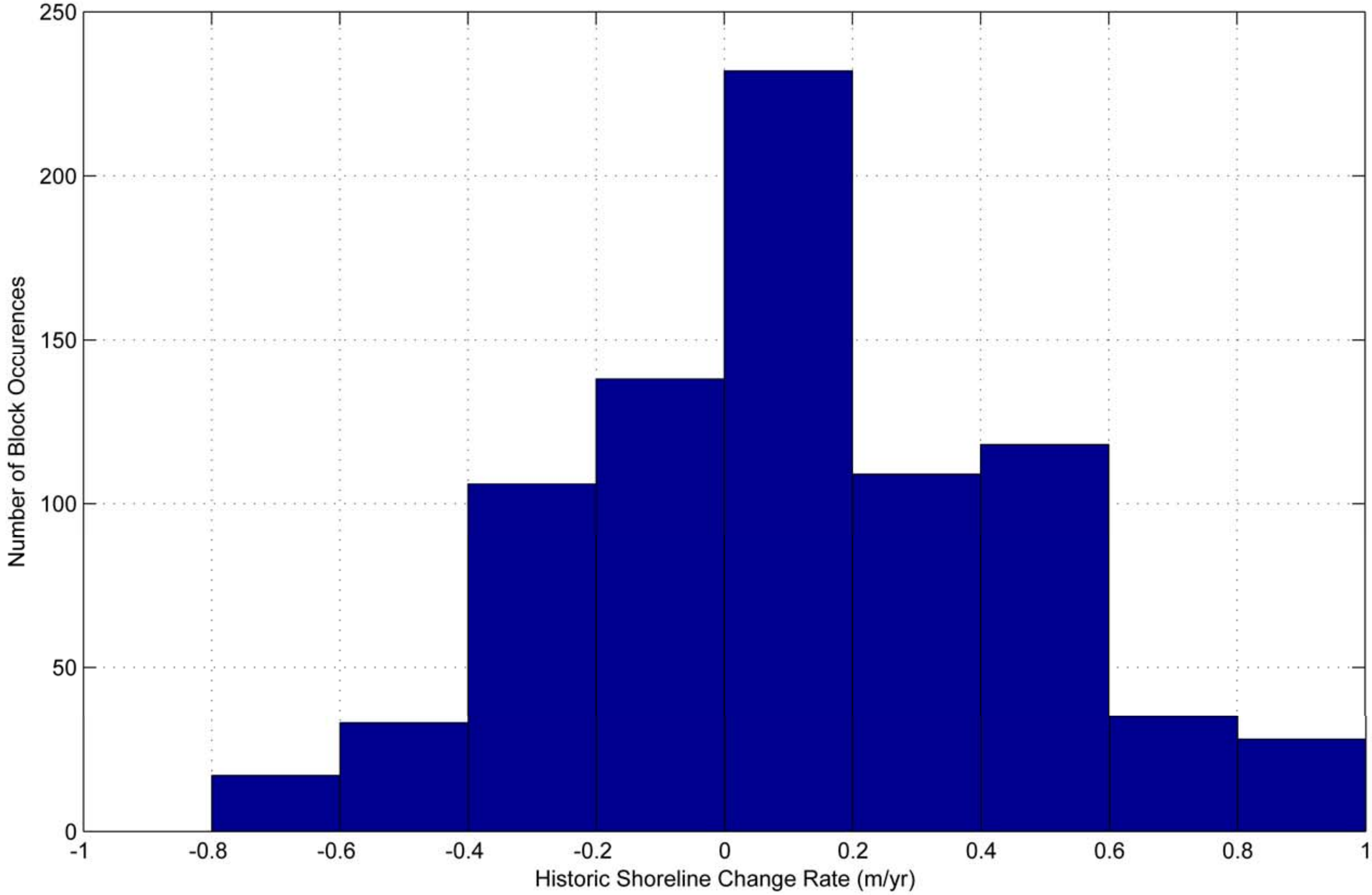


Source / Notes: Dunes and inlet shorelines plotted together. Data from April 1998 LiDAR.

figure 1.9
OPC Sea Level Rise Assessment

Dune Toe Elevation

PWA Ref# 1939



Source: USGS California Coast linear regression shoreline change rates from USGS (Hapke et al 2006).

figure 1.10
OPC Sea Level Rise Assessment

Dune Shoreline Change Rate

PWA Ref# 1939

PWA

	Linear Regression Rate Shoreline Change (m/yr)				Dune Toe Elevation (m NAVD)			
Geologic Unit	Mean	Stnd Dev.	Min	Max	Mean	Stnd Dev.	Min	Max
'Pml'	-0.46	0.33	-0.08	-0.65	3.03	0.83	2.12	3.73
'gr'	-0.27	0.36	-0.06	-0.69	2.12	1.35	0.85	3.54
'Qt'	-0.15	0.10	-0.10	-0.32	2.49	0.49	1.78	2.88
'Mm'	-0.08	0.40	0.49	-0.76	3.11	1.46	0.32	5.72
'Qal'	-0.05	0.30	0.64	-0.62	2.63	1.13	0.32	4.58
'Pu'	-0.03	0.21	0.40	-0.12	4.10	1.22	2.55	5.56
'Mu'	0.03	0.00	0.03	0.03	2.57	0.00	2.57	2.57
'Ku'	0.03	0.15	0.14	-0.15	3.10	1.17	0.65	4.73
'Qm'	0.05	0.30	0.73	-0.57	2.32	1.01	0.42	4.91
'KJf'	0.10	0.24	0.30	-0.61	2.80	0.81	1.47	4.29
'Qs'	0.20	0.35	0.92	-0.68	2.02	1.22	0.04	5.76
'KJfv'	0.24	0.00	0.24	0.24	3.00	1.59	1.16	3.92
'Qc'	0.27	0.00	0.27	0.27	4.50	0.00	4.50	4.50
'Tm'	0.28	0.15	0.42	0.14	1.87	0.54	0.86	3.07
'K'	0.43	0.00	0.43	0.43	2.37	1.03	1.31	5.47

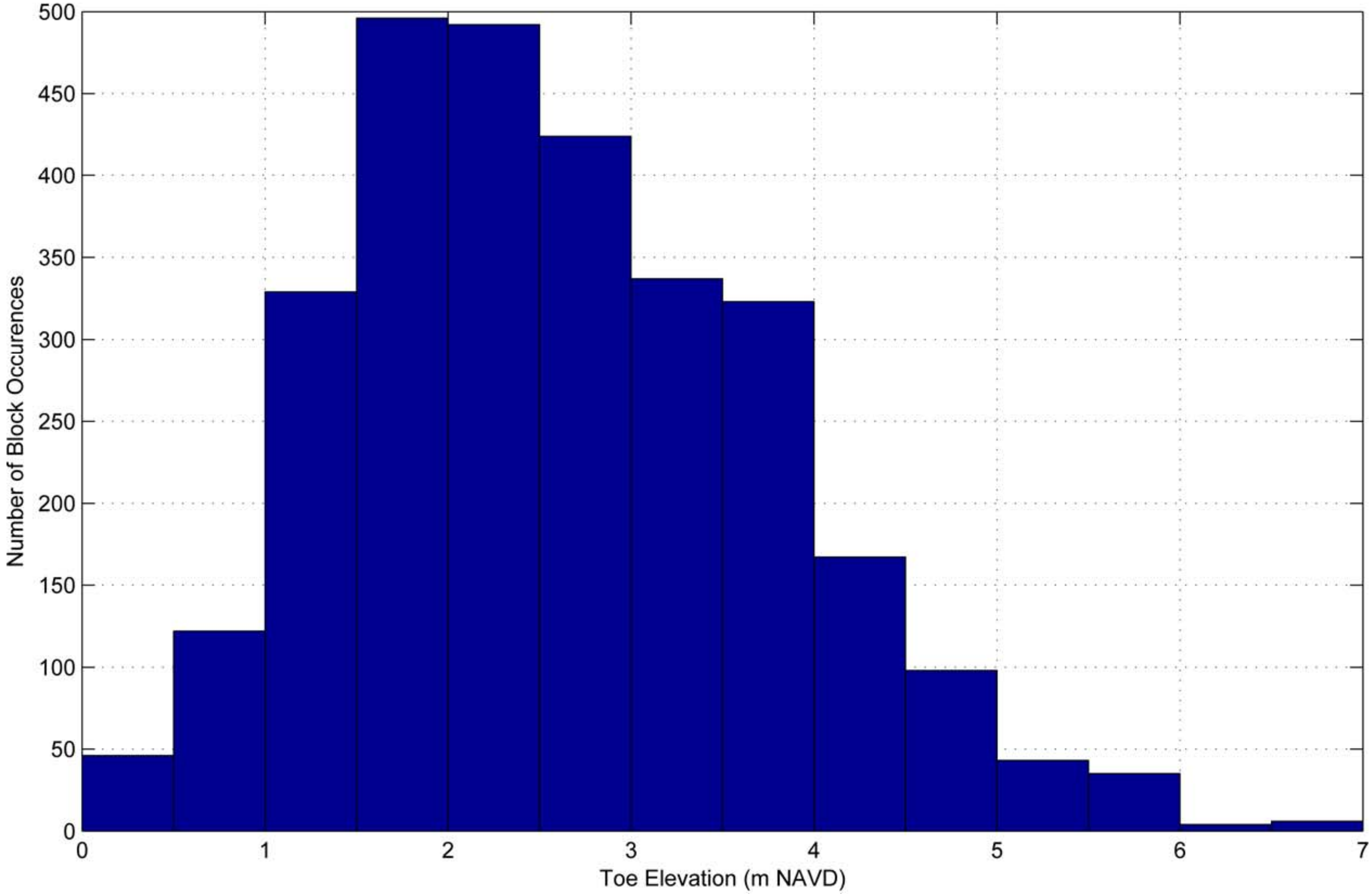
Notes: Negative linear regression rate (LRR) indicates shoreline recession..

figure 1.11
OPC Sea Level Rise Assessment

Dune Statistics by Geologic Unit

PWA Ref# 1939

PWA



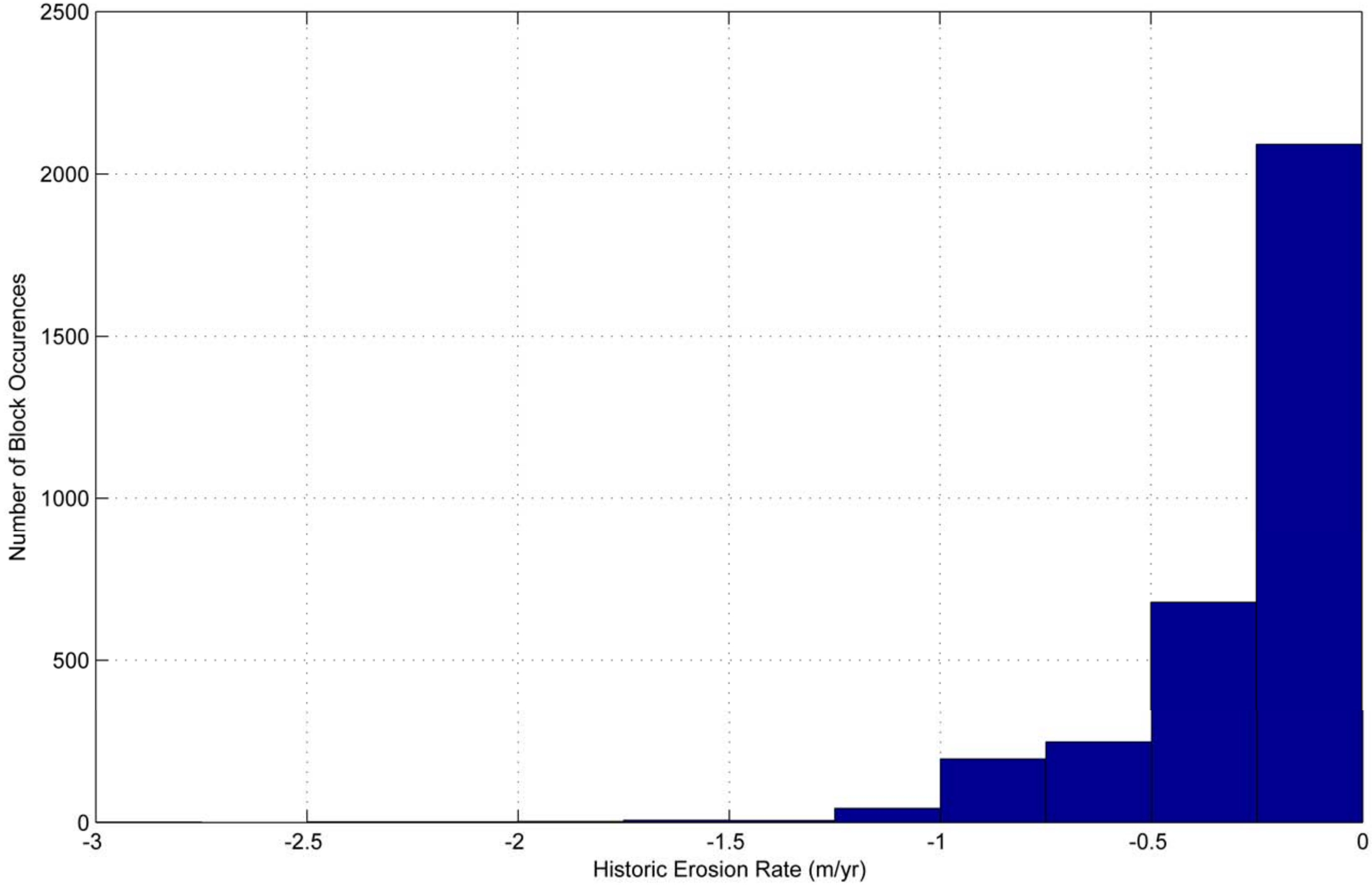
Source: Blocks with Et = 0.0 m NAVD have been removed from dataset.
Cliff toe elevation data derived from April 1998 LiDAR..

figure 1.12
OPC Sea Level Rise Assessment

Cliff Toe Elevation

PWA Ref# 1939

PWA



Source: USGS California Coast end-point erosion rates from USGS (Hapke and Reid 2007).

figure 1.13

OPC Sea Level Rise Assessment

Cliff Shoreline Change Rate

PWA Ref# 1939

PWA

	End-point Erosion Rate (m/yr)				Bluff Toe Elevation (m NAVD)			
Geologic Unit	Mean	Stnd Dev	Min EPR	Max EPR	Mean	Stnd Dev	Min	Max
'QP'	-0.75	0.30	-0.16	-1.24	3.67	1.53	2.25	5.58
'ms'	-0.60	0.21	-0.29	-0.89	3.78	1.60	0.47	5.94
'K'	-0.56	0.40	-0.04	-2.78	2.69	0.93	0.38	5.72
'Qs'	-0.51	0.31	-0.09	-1.21	2.98	1.39	0.42	5.84
'KJf'	-0.48	0.27	-0.05	-1.83	2.91	1.11	0.10	5.93
'm'	-0.38	0.11	-0.22	-0.67	2.77	1.12	1.63	5.53
'Qal'	-0.35	0.28	-0.11	-1.06	3.02	1.27	1.29	5.74
'E'	-0.34	0.09	-0.05	-0.36	2.68	1.09	0.86	4.49
'Pml'	-0.33	0.33	-0.03	-1.63	3.14	1.20	1.15	5.85
'KJfv'	-0.29	0.30	-0.04	-1.00	2.95	1.09	0.84	5.42
'gr'	-0.29	0.29	-0.03	-1.70	2.30	1.36	0.22	5.22
'Pu'	-0.23	0.13	-0.01	-0.98	3.06	0.92	1.00	5.21
'Tvb?'	-0.21	0.08	-0.11	-0.39	1.63	0.72	0.54	3.10
'Mm'	-0.21	0.21	-0.02	-1.14	2.71	1.08	0.04	5.43
'Ep'	-0.21	0.20	-0.06	-1.27	2.58	1.56	0.11	6.55
'Pc'	-0.20	0.08	-0.07	-0.34	2.91	0.55	1.86	3.88
'Qm'	-0.20	0.13	-0.03	-1.04	2.21	1.06	0.03	5.75
'Mu'	-0.20	0.09	-0.03	-0.39	3.02	0.75	0.55	4.27
'Ku'	-0.19	0.11	-0.06	-1.01	2.39	0.95	0.39	6.22
'Kl'	-0.18	0.04	-0.12	-0.22	-	-	-	-
'Ml'	-0.16	0.13	-0.04	-0.48	2.36	0.68	1.48	4.03
'Oligocene marine'	-0.16	0.14	-0.07	-0.41	3.92	0.78	2.94	4.96
'Qt'	-0.16	0.10	-0.05	-0.38	1.95	0.78	0.96	3.74
'Mvb'	-0.16	0.05	-0.07	-0.23	1.82	0.68	0.51	2.93
'ub'	-0.16	0.10	-0.05	-0.50	2.20	0.78	0.25	3.04
'Mvp'	-0.14	0.04	-0.09	-0.23	1.32	0.71	0.12	2.16
'Qc'	-0.12	0.07	-0.03	-0.30	4.09	0.65	2.44	5.25
'Tm'	-0.09	0.07	-0.04	-0.14	2.13	1.20	0.79	4.83
'Mv'	-0.09	0.02	-0.06	-0.12	2.58	0.67	1.62	3.19

figure 1.14
OPC Sea Level Rise Assessment

Cliff Statistics by Geologic Unit

PWA Ref# 1939

PWA

Introduction to the CDIP Monitoring and Prediction (MOP) System

The Coastal Data Information Program (CDIP) is a research group at Scripps Institution of Oceanography that monitors coastal waves and nearshore sand levels on regional scales. The mission of the program is to improve our basic understanding of, and ability to predict, coastal waves and shoreline change.

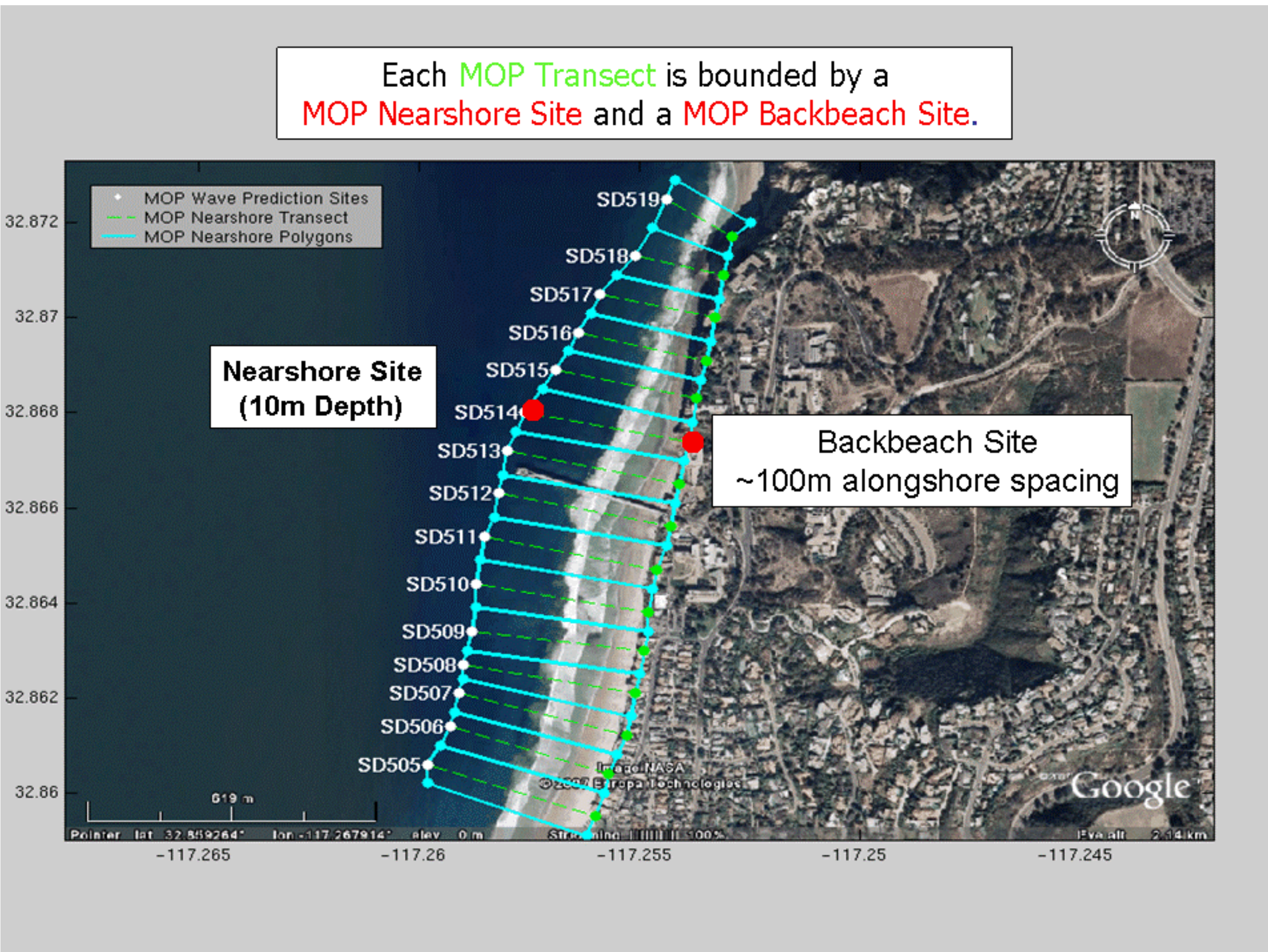
In California, CDIP maintains a network of optimally-placed, directional wave buoys from San Diego to Eureka. The buoy measurements are used to initialize a high spatial resolution (100m x 100m) linear spectral wave propagation model, which accounts for island blocking, refraction and shoaling. The resulting hourly hindcasts and nowcasts of CA coastal wave conditions have a level of accuracy that is not possible with more traditional wind-wave generation models that are initialized with modeled wind fields.

CDIP provides public access to its monitoring-based wave predictions via the CDIP MOnitoring and Prediction (MOP) System. Three types of wave research products are available:

- **MOP Regional Swell Predictions** (waves with periods 8 seconds and longer), which cover the the outer waters of the continental shelf and the Southern California Bight.

- **MOP Inner Waters Sea & Swell Predictions** (wave periods from 2-30 seconds) which cover the waters within ~10 kilometers (6 miles) of the mainland coast. This information is primarily used to support marine safety around harbors and along popular boating routes.

- **MOP Alongshore Sea & Swell Predictions** (wave periods from 2-30 seconds) in 10m (33ft) water depth with ~100m alongshore spacing in Southern California, and 15m (50ft) water depth with ~200m alongshore spacing north of Point Conception.



The alongshore wave predictions are being used in combination with sand level measurements in San Diego County to develop more robust data-adaptive methods for real-time hazard mitigation, regional sediment management (RSM), and long-range shoreline change predictions.

The alongshore MOPs are identified by CA county and numbered from south (downcoast) to north (upcoast). To find the alongshore MOP sites for your favorite CA coast locations go to our Find a MOP page.

MOP System Approach

- Linear Model: each frequency modeled independently.
- Use offshore buoys to predict swell (f=0.04-0.09Hz).
- Use local buoys to predict seas (f=0.09-0.25Hz).
- Weight buoy directional spectra by distance from prediction site.

MOP System Modeling Steps

For Each Wave Frequency Band:

- Define 100% open direction range for each offshore buoy location [Swell/Offshore Buoys Only].
- Smooth buoy data over 3-hour window.
- Estimate directional spectra (MEM).
- Lag time series of deep water directional spectra to the prediction site for 100% open direction range using group velocity (assume deep water everywhere and no islands at this stage).
- Combine lagged directional spectra & weight by distance between buoy and prediction site.
- Transform weighted & lagged deep water directional spectra to sheltered wave energy and directional moments (spectral refraction transformation coefficients).

References

Wave Monitoring in The Southern California Bight. W. C. O'Reilly, R. J. Seymour, R. T. Guza, D. Castel,
Ocean Wave Measurement and Analysis, Proc. 2nd Int. Symp., July 25-28, 1993, pp448-457.

Comparison of Two Spectral Wave Models in the Southern California Bight. W. C. O'Reilly and R. T. Guza,
Coastal Eng., 19, pp263-282, 1993.
