Final

MONTEREY BAY SEA LEVEL RISE VULNERABILITY ASSESSMENT

Technical Methods Report

Prepared for
The Monterey Bay Sanctuary Foundation

June 16, 2014

Santa Cruz Beach Boardwalk, looking west. Photo by E. Vandebroek, January 2014.

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1. INTRODUCTION

1.1 Purpose

This report presents technical documentation of the methods used to map erosion and coastal flood hazards under various future climate scenarios for the Monterey Bay, California coastline. This report supplements the metadata associated with each geospatial dataset by documenting, in detail, the input data and methods used to generate these hazard zones.

This report was prepared by Elena Vandebroek, P.E., David Revell, Ph.D. (Project Manager), and To Dang, Ph.D., with technical oversight by Bob Battalio, P.E. (Project Director).

1.2 Background

ESA PWA, the Monterey Bay Sanctuary Foundation (MBSF), and others are working with local communities to assess Monterey Bay's vulnerability to potential future impacts of sea level rise. Monterey Bay is an extremely valuable economic and environmental resource along California's central coast. A large portion of the Monterey Bay shoreline is currently experiencing coastal erosion, which is expected to be exacerbated by accelerated sea level rise. Similarly, coastal flooding will also worsen with sea level rise. The MBSF contracted ESA PWA to assess the potential impacts of sea level rise on coastal erosion and flooding.

As part of this project, MBSF and ESA PWA identified relevant stakeholders and science experts and established a Technical Advisory Group (TAG). The TAG includes The Southern Monterey Bay Coastal Erosion Workgroup as well as other experts and stakeholders from Northern Monterey Bay. In October 2012 the TAG convened and provided the MBSF and ESA PWA with input on available data sources, sea level rise scenarios, methods, and formats of deliverables. In January 2014 ESA PWA and the MBSF presented and discussed draft hazard zones with the TAG.

1.3 Previous Coastal Hazards Analysis

Multiple coastal hazards assessments already exist for the Monterey Bay study area:

- FEMA flood hazard maps, which are used for the National Flood Insurance Program, present coastal and fluvial flood hazards. However, these maps were published in the 1980s are believed to underestimate coastal flood hazards. FEMA is currently updating coastal flood hazard maps according to the 2005 Pacific Coast Guidelines (FEMA 2005). The extent of flood hazards is expected to increase because of changes in FEMA methodology and sea level rise since the 1980s. These maps will only assess existing hazards and will not consider future erosion or projected sea level rise.

- In 2012, the NOAA Coastal Services Center created the Digital Coast Sea Level Rise and Coastal Flooding Impact Viewer ("NOAA SLR Viewer," available at http://www.csc.noaa.gov/slr/viewer/) for the entire U.S. coastline. Users of the viewer can view inundation of existing high tide (Mean Higher High Water) and see how this daily inundation area will change with 1-ft increments of sea level rise. A "confidence" layer, based on uncertainty in the LiDAR surface and modeled tidal surface, classifies hazard areas as high or low confidence. The viewer displays qualitative water depth and classifies disconnected low-lying areas separately. As of March 2014, the viewer does not present storm hazards such as extreme tides and wave run-up, and coastal erosion is not considered.

- Tsunami inundation maps, developed by CalEMA, the University of Southern California, and the California Geological Survey, are also available for the entire state of California.

- In 2009, Philip William and Associates, Ltd. (now ESA PWA) was funded by the Ocean Protection Council to provide the technical hazards analysis in support of the Pacific Institute report on the “Impacts of Sea Level Rise to the California Coast” (“The Pacific Institute study,” PWA 2009). In the course of this work, ESA PWA projected future coastal flooding hazards for the entire state based on a review of existing FEMA hazard maps. In addition, ESA PWA projected future coastal erosion hazard areas for the northern and central California coastline. These hazard areas were used in the Pacific Institute study, which evaluated potential socio-economic impacts of sea level rise. These maps completed as part of the Pacific Institute study specifically stated that the results were not to be used for local planning purposes given the use of “best statewide available data sets”; however, the modeling methods (Revell et al 2011) were developed to be readily re-applied as improved regional and local data became available.

The present study has improved the methods from the Pacific Institute Study and applied them to the Monterey Bay study area with higher resolution local data and review by local experts. The net result of these improved methods has been to produce projections of future coastal hazards that are suitable to supporting local planning processes (e.g. LCP updates, General Plans, permit applications).

1.4 Monterey Bay Study Area

This study assessed coastal hazards along approximately 60 miles of coastline from Punta de Año Nuevo in southern San Mateo County, through Santa Cruz County, to Wharf II in the City of Monterey in Monterey County (Figure 1). Northern Santa Cruz County, from Año Nuevo to Natural Bridges State Park is characterized by a series of relatively undeveloped eroding sea cliffs. Highway 1 runs along the coast through agricultural fields (primarily brussel sprouts and artichokes). The sea cliffs are intersected by a series of low-lying pocket beaches and coastal lagoon systems. Northern Monterey Bay is heavily developed, with significant development along the cliff edges and in the low lying lagoon systems (Cities of Santa Cruz, Capitola, and Aptos). Extensive cliff armoring, seawalls, and levees reflect the existing coastal hazards that are present along this stretch of coast. A series of high, stable, sandy bluffs characterize the reach between New Brighton State Beach and Sunset State Beach. Sunset State Beach through Southern Monterey Bay is an actively eroding dune-backed shoreline containing two major rivers and Elkhorn Slough. The southern Monterey Bay has a history of sand mining which exacerbates coastal erosion (Thornton et al 2006).

2. SUMMARY OF GIS DELIVERABLES

This section summarizes the GIS deliverables developed as a result of this work and points to the relevant sections in this document that describe how each was developed. An example map is included for each type of data. Hazard zones were developed for existing conditions (2010) and three planning horizons (2030, 2060, and 2100) based on guidance from the TAG. Various future sea level rise and erosion scenarios were assessed for each type of hazard. These scenarios are summarized in section 2.1 and are described in more detail in Sections 4.1 and 8.1. All GIS deliverables are provided in the NAD 1983 datum and UTM Zone 10N projection. Horizontal units are in meters.

Dune Erosion Hazard Zones (Section 8.1 and 8.2, Figure 2):

These zones represent future dune (sandy beach) erosion hazard zones, incorporating site-specific historic trends in erosion, additional erosion caused by accelerating sea level rise, and (in the case of the “storm erosion hazard zones”) the potential erosion impact of a large storm wave event. The inland extent of the hazard zones represent projections of the future crest of the dunes for a given sea level rise scenario and planning horizon. At each planning horizon, the hazard zones for all scenarios are overlaid into a single “spatially aggregated” layer that counts the number of scenarios that are projected to be hazardous at a particular location. The spatial aggregation data set is intended to be a planning tool that helps identify the relative risk by bracketing some of the uncertainty associated with which areas will be hazardous for all sea level rise and wave scenarios and, for a given planning horizon, which areas may only be hazardous for the worst case scenarios.

- Long-term erosion hazard zones (does not include effect of a 100-year storm)
  27 polygon shapefiles: 3 planning horizons x 3 SLR scenarios x 3 future erosion scenarios

- Storm erosion hazard zones
  30 polygon shapefiles: 3 planning horizons + existing conditions x 3 SLR scenarios x 3 future erosion scenarios

- Spatially aggregated erosion hazard zones (see Section 10 for more detail)
  3 polygon shapefiles: one for each planning horizon

Cliff Erosion Hazard Zones (Section 8.3 and 8.4, Figure 3):

These zones represent future cliff erosion hazard zones, derived by incorporating site-specific historic trends in erosion, additional erosion caused by accelerating sea level rise, and a safety buffer to account for the along-shore variability in erosion rates (an indicator of extreme erosion events/block failures). The inland extent of the hazard zone represents the future cliff edge projected for each planning horizon and future scenario. At each planning horizon, the hazard zones for all scenarios are overlaid into a single “spatially aggregated” layer that counts the number of scenarios that are projected to be hazardous at a particular location. The spatial aggregation data set is intended to be a planning tool that helps identify the relative risk by bracketing some of the uncertainty associated with the hazard zones.

- Long-term erosion hazard zones (no 100-year storm)
  18 polygon shapefiles: 3 planning horizons x 3 SLR scenarios x 2 future erosion scenarios

- Storm erosion hazard zones
  20 polygon shapefiles: 3 planning horizons + existing conditions x 3 SLR scenarios x 2 future erosion scenarios

- Spatially aggregated erosion hazard zones (see Section 10 for more detail)
  3 polygon shapefiles: one for each planning horizon

Rising Tides Inundation Zones (Section 9.1, Figure 4a and b)

These zones show the area and depth (in meters) of inundation caused simply by rising tide and groundwater levels (not considering storms, erosion, or river discharge). The water level mapped in these inundation areas is the Extreme Monthly High Water (EMHW) level[1], which is a high water level that is reached approximately once a month. These zones do not, however, consider coastal erosion or wave overtopping, which may change the extent and depth of regular tidal flooding in the future.

- Potential inundation area of Extreme Monthly High Water
  10 polygon shapefiles: existing conditions and 3 planning horizons x 3 SLR scenarios

  Note: There are two types of inundation areas: (1) areas that are clearly connected over the existing digital elevation through low topography, (2) and other low-lying areas that don't have an apparent connection, as indicated by the digital elevation model, but are low-lying and flood prone from groundwater levels and any connections (culverts, underpasses) that are not captured by the digital elevation model. This difference is captured in the "Connection" attribute (either "connected to ocean over topography" or "connectivity uncertain") in each geospatial dataset. We recommend these be mapped as separate colors, similar to the NOAA SLR Viewer (described in Section 1.3). Some improvement to this data set based on enhanced connectivity data (e.g. culverts, tide gates) will be coming following future refinements funded as part of the Monterey County LCP grant from the Ocean Protection Council.

- Depth of water within the rising tide inundation zone (in meters)
  *20 rasters (5 meter cell size): existing conditions and 3 planning horizons x 3 SLR scenarios x two types**

  ** For the depth rasters the two types of inundation areas (described in the bullet above) are split into two raster files. Ideally, these would be displayed at the same time in a web viewer with different color ramps.*

  Note: A value of 999 represents areas that are already permanently wet under existing conditions.

- Spatially aggregated rising tide hazard zones (see Section 10 for more detail)
  3 polygon shapefiles: one for each planning horizon

Coastal Storm Flood Hazard Zones (Section 9, Figure 5)

These hazard zones depict flooding caused by a coastal storm. The processes considered include (1) storm surge (a rise in the ocean water level caused by waves and pressure changes during a storm), (2) wave overtopping (waves running up over the beach and flowing into low-lying areas, calculated

[1] Extreme Monthly High Water is approximately 33 cm (13 inches) above Mean Higher High Water at the Monterey tide gage or 2.0 meters (6.6 feet) NAVD88.

using the maximum historical wave conditions), (3) extreme lagoon water levels which can occur when lagoon mouths are closed and fill up during rainfall events, and (4) additional flooding caused by rising sea level in the future. This hazard zone also takes into account areas that are projected to erode in the future, sometimes leading to additional flooding through new hydraulic connections between the ocean and low-lying areas. These hazard zones do NOT consider upland fluvial (river) flooding and local rain/run-off drainage, which likely play a large part in coastal flooding, especially around coastal confluences where the creeks meet the ocean.

- Storm flood hazard zones
  10 polygon shapefiles: existing conditions and 3 planning horizons x 3 SLR scenarios

  There are two types of storm flood areas: (1) areas that are clearly connected over the existing digital elevation through low topography, (2) and other low-lying areas that don't have an apparent connection, as indicated by the digital elevation model, but are low-lying and flood prone from groundwater levels and any connections (culverts, underpasses) that are not captured by the digital elevation model. This difference is captured in the "Connection" attribute (either "connected to ocean over topography" or "connectivity uncertain") in each geospatial dataset. We recommend these be mapped as separate colors.

- Spatially aggregated coastal storm flood hazard zones (see Section 10 for more detail)
  3 polygon shapefiles: one for each planning horizon

Spatial Aggregation Relative Risk Zones (Section 10, Figure 6)

These data layers represent the overlap of all of the scenarios and hazards mapped for a given planning horizon. The intent is to represent the uncertainty associated with the various projections by clearly illustrating which areas are always hazardous at a given time horizon and which areas are only hazardous during more extreme scenarios of sea level rise and storminess. To the extent that this project is used to make individual permit decisions is our RECOMMENDATION that this spatial aggregation layer be used to evaluate the potential coastal hazards.

2.1 File Naming Convention

The naming conventions for the GIS deliverables are based on hazard zone type, erosion projection type (if applicable), future erosion scenario (if applicable), sea level rise scenario, and planning horizon, as follows:

Dune and cliff erosion hazard zones:
Hazard zone type + _ + erosion projection type +_+ future erosion scenario +_+ sea level rise scenario + planning horizon

Flood hazard zones:
Hazard zone type + _ + sea level rise scenario + planning horizon

Hazard zone types:

dhz –	Dune erosion hazard zone
dhz_aggr –	Spatially aggregated dune erosion hazard zones
chz -	Cliff erosion hazard zone
chz_aggr –	Spatially aggregated cliff erosion hazard zones
tide_area –	Rising tide (Extreme Monthly High Water) inundation area

tide_area_aggr -	Spatially aggregated rising tide zones
dep –	Rising tide inundation zone depth in areas with a definite connection to ocean tides
dep_l –	Rising tide inundation zone depth in low-lying areas where the connectivity to the ocean is uncertain.
coastal_floodhz -	Coastal storm flood hazard zone
coastal_floodhz_aggr -	Spatially aggregated coastal storm flood hazard zone

Erosion projection type (only applies to dune and cliff erosion hazard zones):

longterm –	A continuation of historic erosion with additional erosion caused by sea level rise. Does not include potential impacts of a large storm.
wstorm –	Includes long-term erosion and the potential erosion of a large storm event (e.g. 100-year storm)

Future erosion scenarios (only applies to dune and cliff erosion hazard zones):

nochange –	A continuation of existing wave climate and sand mining
stopmining –	Stop sand mining (only applies to southern Monterey Bay)
stormier –	Increased storminess (doubling of El Niño storm impacts in a decade)

Sea level rise scenarios (Section 4.1):
ec – Existing conditions (2010 water level)
s1 – Low sea level rise (41 cm by 2100)
s2 – Medium sea level rise (88 cm by 2100)
s3 – High sea level rise (159 cm by 2100)

Planning horizons (Section 4.1):
2010 (Existing conditions)
2030
2060
2100

Example: The *long-term* coastal erosion hazard zone at *2100* with medium *sea level rise* (s2) and cessation of sand mining (*stopmining*) is named “dhz_longterm_stopmining_s22100.shp”

A complete list of GIS deliverables is provided in Appendix 1.

3. DISCLAIMER AND USE RESTRICTIONS

Funding Agencies

These data and this report were prepared as the result of work funded by The California Coastal Conservancy, the Natural Capital Project, and the City of Capitola (the “funding agencies”). It does not necessarily represent the views of the funding agencies, its respective officers, agents and employees, subcontractors, or the State of California. The funding agencies, the State of California, and their respective officers, employees, agents, contractors, and subcontractors make no warranty, express or implied, and assume no responsibility or liability, for the results of any actions taken or other information developed based on this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. These study results are being made available for informational purposes only and have not been approved or disapproved by the funding agencies, nor has the funding agencies passed upon the accuracy, currency, completeness, or adequacy of the information in this report. Users of this information agree by their use to hold blameless each of the funding agencies, study participants and authors for any liability associated with its use in any form.

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4. DATA SETS

4.1 Planning Horizons and Sea Level Rise Projections

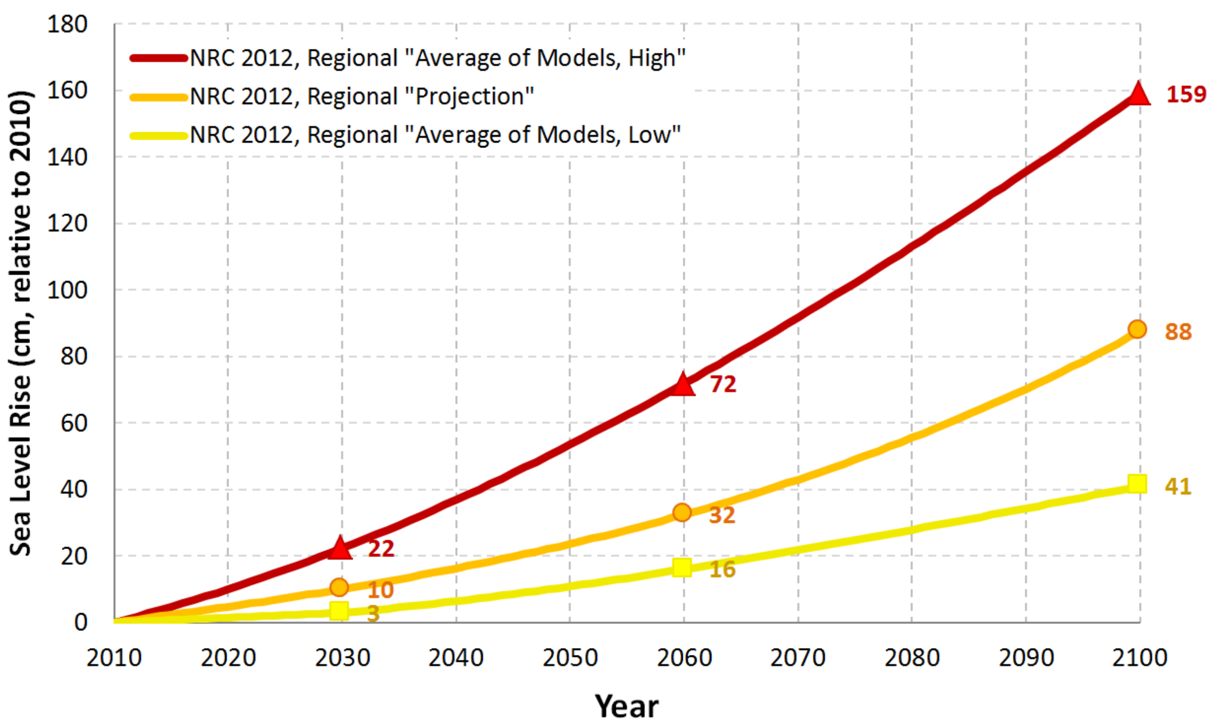
The planning horizons (2030, 2060, and 2100) were selected based on input from the TAG. Many general plans are currently planning for 2030. The intermediate planning horizon, 2060, was selected because it aligns with the lifespan of a typical building constructed as part of the 2030 plan. Finally, 2100 is the longest planning horizon since this is the last year that most sea level rise projections and guidance consider. This horizon is roughly a typical structural life expectancy for large infrastructure projects, such as bridges, which often prove to be significant constraints to large scale adaptation planning and nature based adaptation solutions. These planning horizons do not address any specific timeline for plans/policies such as General Plans or Local Coastal Plans that use the current year as a baseline and plan for 25, 50, 75, or 100 years into the future.

The sea level rise scenarios used in this project are based on the recent study by the National Research Council (NRC, 2012). The low, medium, and high sea level rise scenarios use the "Average of Models, Low," "Projection," and "Average of Models, High," regional sea level rise amounts for San Francisco (NRC, 2012, Table 5.3). This regional projection includes an adjustment for vertical land motion (subsidence of 1mm/yr ± 1.5 mm/yr) that is applied for the California coast south of Cape Mendocino. Draft sea level rise policy guidance from the California Coastal Commission (CCC 2013) recommends using the regional values reported in NRC 2012. Since NRC 2012 provides sea level rise amounts relative to 2000, rather than 2010 (the starting year for this study), a 3rd order polynomial curve was fit to the provided values to estimate sea level rise at 2030, 2060, and 2100 relative to 2010. The sea level rise at each planning horizon is shown in Table 1 and marked in Figure 7.

Table 1. Sea Level Rise Projections, relative to 2010

Year	*Low SLR*	*Medium SLR*	*High SLR*
2030	3 cm (1.1 inches)	10 cm (4 inches)	22 cm (8.8 inches)
2060	16 cm (6.3 inches)	33 cm (12.8 inches)	72 cm (28.3 inches)
2100	41 cm (16.1 inches)	88 cm (34.5 inches)	159 cm (62.6 inches)

Figure 7 - Sea Level Rise Scenarios



4.2 Aerial Imagery

Digital Orthophotography

ESA PWA downloaded the aerial mosaics from the NOAA Digital Coast Data Access Viewer (NOAA, 2012b). This imagery is the California Coastal ADS40 4-Band 8 bit collected from May to October 2010 as part of the 2009 – 2011 Coastal LiDAR project. This imagery is reported to have 30 cm resolution with a horizontal accuracy of 2 meters or better at the 95% confidence level. This imagery was downloaded from the USDA GeoSpatial Data Gateway and reportedly has 1 meter resolution and ± 6 meter horizontal accuracy.

Oblique Aerial Imagery

ESA PWA used the California Coastal Records Project website to identify coastal armoring and other relevant structures along the coast. These photos were accessed through the project website (Adelman and Adelman, 2013). The most recent photos were collected in October 2013.

4.3 Digital Elevation Models

2009 – 2011 California Coastal Conservancy Coastal LiDAR Project Hydro-Flattened Bare Earth DEM

Downloaded from the NOAA Digital Coast Data Access Viewer (NOAA, 2012a). LiDAR data was collected in May through October 2010 for the Monterey Bay study area. The LiDAR data has 1 meter resolution with a horizontal accuracy of ± 50 cm and a vertical accuracy of ± 9 cm. The LiDAR data was reclassified, filtered, edited, and hydro-flattened by the DEM creators using 3D hydro breaklines to develop the final DEM[2]. This was the primary DEM used for conducting topographic analysis and mapping coastal erosion and flood hazard zones.

1998 Airborne LiDAR Assessment of Coastal Erosion Project

Downloaded from the NOAA Digital Coast Data Access Viewer (NOAA, 2012c). LiDAR data was collected in April 1998, after the 1997-1998 El Niño winter. The LiDAR data has 3 meter resolution with a horizontal accuracy of ± 80 cm and a vertical accuracy of ± 15 cm, and was not controlled for tide. This dataset was used to fill in small gaps in the 2009-2011 DEM (above) in the Northern Santa Cruz County stretch of the study area.

California State University Monterey Bay (CSUMB) Seafloor Mapping Lab

Downloaded from the CSUMB data library for Monterey Bay Data (http://seafloor.otterlabs.org/SFMLwebDATA_mb.htm). Most of the surveys were conducted in fall 2008 and 2009 as part of the California Seafloor Mapping Program. Between Sand City and Wharf II the surveys were conducted between 2000 and 2004. The surveys used in this study cover Monterey Bay from Moss Landing to the City of Monterey. The digital elevation models are at provided at 2 or 3 meter resolution and have a reported horizontal accuracy of ± 2 m and vertical accuracy of 20 cm (highly depth-dependent).

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[2] Detailed metadata describing DEM development is available on the NOAA Digital Coast Data Access Viewer at this link: http://csc.noaa.gov/dataviewer/webfiles/metadata/ca2010_coastal_dem.html (Accessed April 2, 2013).

USGS Swath Bathy Surveys of the Monterey Bay Area

Downloaded from the USGS Data Series (http://pubs.usgs.gov/ds/514/, Ritchie et al 2010). Surveys were conducted between August and December 2009 as part of the California Seafloor Mapping Program. The surveys cover Monterey Bay from Point Año Nuevo to Moss Landing. The digital elevation models are at provided at 2 m resolution and have a reported horizontal accuracy of ± 2 m.

4.4 Geology

A GIS compilation of previously published hardcopy geology maps was downloaded from the USGS website (Ludington et al. 2005). The statewide dataset is based on the Geologic Map of California by Jennings et al, 1977. This map was revised and simplified based on a review by Dr. Jerry Weber and Dr. Gary Griggs, Professors of Earth Sciences at the University of California Santa Cruz. Table 2 lists the geologic units and Figure 8 shows the spatial distribution of coastal geology. The geology map was used in development of the backshore classification and division of the coast into analysis blocks.

Table 2. Geologic Units in Coastal Monterey Bay

Geologic Unit	Description	Average Erosion Rate	Standard Deviation of Erosion Rates (along shore)
P-Light	Pleistocene Sand	10 cm/year	21 cm/yr
P	Purisima Formation	12 cm/year	9 cm/yr
Q	Quaternary*	25 cm/year	--
SC-M	Santa Cruz Mudstone	9 cm/year	6 cm/yr

** Only one study block was assigned this geology so assigned the alongshore variability of the adjacent SC-M.*

4.5 Tides

The NOAA Monterey tide gage (#9413450) tidal datum was selected because it is the tide gage nearest to the Monterey Bay study area (Figure 1). The primary use of this datum was for shoreline analysis and flood mapping. Mean high water (MHW) was used as the representative elevation for shoreline change analysis (see Section 5.2). Extreme Monthly High Water (EMHW) was used for the rising tides hazard zones (see Section 9.1). The 100-year water level was used in the coastal storm flood hazard mapping, with some adjustments as described in see Section 9.2. Tide gauge measurements in Monterey do not capture the wind and wave set up during storm events that has been observed along Northern Monterey Bay in Santa Cruz.

Table 3. Monterey Tidal Water Levels

Tide	meters, NAVD88	feet, NAVD88
100-year High Water Level*	2.475	8.12
Highest Observed Water Level (Jan 27, 1983)	2.444	8.02
Extreme Monthly High Water**	2.002	6.57
Mean Higher High Water	1.669	5.48
Mean High Water	1.455	4.77
Mean Tide Level	0.916	3.01
Mean Sea Level	0.905	2.97
Mean Low Water	0.376	1.23
Mean Lower Low Water	0.043	0.14
NAVD88	0	0
Lowest Observed Water Level	-0.687	-2.25
100-year Low Water Level*	-0.715	-2.35

Notes: The tidal datum analysis period was 1983 - 2001 at National Oceanic and Atmospheric Administration station #9413450; NAVD88 = North American Vertical Datum of 1988. Sources: Tidal Datums (NOAA, 2005b)
* from NOAA Tides & Currents “Exceedance Probability Levels and Tidal Datums,” available at http://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=9413450. Accessed 1/3/2014.
** Extreme Monthly High Water was calculated by averaging the maximum monthly high water for all monthly data available at the Monterey tide gage (464 months).

4.6 Waves

Offshore Wave Data

A 17-year offshore wave time series (January 1996 – February 2013) of 9-band wave data (wave height, period, and direction) was developed using data from the NDBC Monterey buoy (#46042, CDIP #185) with data gaps filled with the CDIP Point Reyes buoy (CDIP #029). This time series was used to develop nearshore wave data for input to the coastal erosion model (Section 6).

Wave Models

Wave models from three different sources were combined for this study. These models were used to develop wave transformation matrices for 44 points along the Monterey Bay study area (Figure 9). Ed Thornton provided wave transformation matrices for 20 locations between the City of Monterey and the Santa Cruz Harbor (Figure 9, Appendix 2). These matrices were based on a modified version of the linear refraction model by Dobson 1967. Sea Engineering, Inc. used SWAN to develop wave transformation matrices for 15 locations between Elkhorn Slough and 4-Mile (Appendix 3). An existing SWAN model developed by ESA PWA was calibrated using the northern-most transformation point from Sea Engineering, Inc, which overlapped with the ESA PWA in-house model. This calibration process is described further in Appendix 4.

4.7 Historic Shoreline Positions

USGS National Assessment of Shoreline Change for Sandy Shorelines

Downloaded from the USGS website (Hapke et al 2006). This assessment calculated short- (1970s to 1998) and long-term (1870s to 1998) shoreline change rates for sandy shorelines along the California

Coast. The report includes a GIS database containing four historic shorelines and other GIS files used to calculate the rates of change. The shoreline position error for each time period ranged from 1.5 to 17.8 meters. The most recent shoreline used in this study was extracted from April 1998 LiDAR, which was immediately after the 1997-1998 El Nino. Inclusion of this shoreline likely resulted in over-estimation of long- and short-term erosion rates. Section 5.2 discusses how these erosion rates were updated with three additional recent non-post storm LiDAR datasets.

USGS National Assessment of Cliff Erosion

Downloaded from the USGS website (Hapke and Reid 2007). This assessment calculated long-term cliff edge erosion rates (end point rate between 1930s and 1998) along the California Coast. The report includes a GIS database containing two historic cliff edges and other GIS files used to calculate the rates of change. Hapke et al provided ESA PWA with a revised version of the cliff edges which addressed some rectification issues along the Northern Santa Cruz County cliffs. The annualized retreat rate uncertainty for California cliff edges was reported at 0.2 m/year, with the major uncertainties attributed to georectification of historic (1930s) T-Sheets. Section 5.2 discusses how these erosion rates were updated with an additional cliff edge digitized from recent LiDAR.

4.8 Coastal Armoring Database

In early 2012, ESA PWA designed a coastal armoring geodatabase for the California Ocean Science Trust, California Coastal Commission, and State Coastal Conservancy (ESA PWA 2012a). This geodatabase was designed to update an earlier armor database (J. Dare 2005) with additional information, recent changes to the coast, and the ability to track permit status of coastal structures. In late 2012 the California Coastal Commission populated the geodatabase for Santa Cruz County and provided this updated database to ESA PWA for this study.

5. TOPOGRAPHIC ANALYSIS

5.1 Beach and Cliff Profiles

Beach and cliff profiles were analyzed to identify topographic features pertinent to the coastal erosion analysis. Profiles were extracted at 100 meter along-shore spacing from the three digital elevation models described in Section 4.3 at 1 meter point spacing. These profiles were then analyzed in elevation view using an interactive, custom-built MATLAB tool to identify various geomorphic features including the foreshore beach slope (approximately between mean low water and mean high water) and back beach (dune, seawall) toe and crest elevations. All geomorphic feature locations were then mapped in plan-view over high resolution aerial imagery to verify the profile-based interpretation. In some areas, especially where development encroaches on the beach and the profile shows a consistently flat beach surface, a “dune crest elevation” was estimated by choosing a point directly shoreward of development.

5.2 Shore Change and Cliff Edge Erosion Rates

Shoreline change rates and cliff edge erosion rates were compiled from a variety of sources for the shores of Monterey Bay. These datasets are summarized in Table 4 and Table 5, ordered by priority (top priority listed first). In general, the more site-specific and detailed analyses were given priority. Figure 10 presents the erosion rates from each of these datasets, including those considered but not used.

Table 4. Data Sources for Shoreline Change Rates

Source	Description	Dates
Thornton 2006	Dune top recession rates along Southern Monterey Bay	1984, 1997, 1998, 2004
ESA PWA 2012 for Scott Creek Beach	Linear regression rate of change for wet/dry shoreline (7 inches/year).	1853 to 2008 (10 measurements)
ESA PWA 2012 for Waddell Creek Beach	Linear regression rate of change for wet/dry shoreline from (11 inches/year).	1853 to 2002 (10 measurements)
This study	ESA PWA updated the USGS 2006 National Assessment of Shoreline Change[3] with a 2010 MHW shoreline extracted from recent LIDAR. Linear regression rates measured at 100 meter spacing along-shore.	1932/1933, 1945/1952/1953/1954, 1998, and 2010

Table 5. Data Sources for Cliff Edge Erosion Rate

Source	Description	Dates
Moore and Griggs, unpublished	ESA digitized erosion rates from a hardcopy dissertation manuscript and averaged these rates by study block.	1953 to 1994
Moore and Griggs 2002	Published study with in-depth analysis of erosion rates at four locations in Northern Monterey Bay.	1953 to 1994
Griggs, Patsch, and Savoy 2005	G. Weber estimated the erosion rate along the south coast of Año Nuevo from oblique aerial images and site observations.	1973 to 2000
This study	ESA PWA updated USGS 2006 with a 2010 cliff edge interpreted from recent LIDAR. Linear regression rates measured at 100 meter spacing along-shore. This analysis excluded transects across coastal armoring.	1932, 1998, 2010
USGS 2008	The National Assessment of Shoreline Change[4], not updated for 2010. Used in places where the 2010 LiDAR had gaps and no other datasets were available.	1932 to 1998

[3] GIS shorelines available at; http://pubs.usgs.gov/of/2006/1251/#gis.
[4] Original GIS cliff edges available at http://pubs.usgs.gov/of/2007/1112/#gis. However, USGS provided ESA PWA with a spatially shifted version of the cliff edges to allow comparison with recent LiDAR.

6. BACKSHORE CHARACTERIZATION

ESA PWA developed an updated backshore characterization based on the initial offshore baseline from the Pacific Institute study. The baseline was segmented at 500 meter (~1500 feet) spacing ("Blocks") to conduct the coastal modeling at a scale appropriate to decision making. An offshore baseline was divided into blocks based on backshore type (dune, inlet, cliff), armoring, and geology. The datasets described in Section 4 and the results from the topographic analysis (Section 5) were summarized into each of these alongshore blocks (268 in total). Each block was assigned a set of parameters including backshore type (dune/cliff/inlet), presence of coastal armor, geology, erosion rates, median/minimum toe elevations, dune/cliff crest elevation, beach slope, foreshore slope, and the 100-year water level (see Section 7.2, below).

Following the initial summary of existing data sets into the blocks, the backshore characterization was adjusted in a number of specific regions using engineering judgment and observations of past erosion hazards:

- Blocks that showed accretion but are backed by at least 50% coastal armoring were assigned a historic shoreline erosion rate of 0 because the accretion processes that occurred prior to construction are expected to differ from the processes after construction. In these cases (14 blocks), we assume that this site had previously experienced episodic erosion that is not represented in average annual regression rates. It is also anticipated that over time as the structure begins to interact with waves more frequently that there will be an acceleration of erosion. Also, armored shorelines can appear to "accrete" due to placement of additional shoreline armoring such as additional rocks, or by the exposure of the lower foundation which often slopes seaward.

- Between the Pajaro River and the Salinas River the shoreline showed high rates of accretion (as much as ~0.8 meters/year). Accretion signals in this stretch were capped at 0.25 m/year. We expect that the sediment demand created by sea level rise will consume more available sand and the accretion rates will decrease.

- Blocks lacking cliff erosion rates were assigned the average erosion rate of the four closest study blocks (usually 2 adjacent blocks on either side).

- The shoreface slope for blocks 213 and 214, just south of Elkhorn Slough were very steep due to the Monterey Submarine Canyon. While the Canyon affects wave heights and the existing slope, we anticipate that a flatter slope will develop as the shore recedes. Therefore, these blocks were assigned the foreshore slope from block 215.

- Cliff blocks lacking total water level data (due to submerged toes or lacking beaches to calculate run-up on) were assigned total water parameters from the nearest block with water level data available.

- The 100-year total water levels south of Moss Landing (Blocks 215, 217, 218, and 219) did not exceed the backshore toe elevation (which is known to have been exceeded in the past). Therefore, the 100-year TWL from Blocks 216 or 220 were assigned to these blocks.

7. WAVE MODELING AND RUNUP CALCULATIONS

7.1 Nearshore Wave Transformation Modeling

The nearshore transformation matrices were used to transform the 17-year time series of offshore waves to nearshore wave height and period. The transformation matrices and wave time series are described in Section 4.6. These nearshore time series were then used to calculate a time series of runup for each along-shore analysis block (next section).

This approach provides a reasonable approximation of wave propagation from the open ocean into the Monterey Bay coast by accurately transforming the powerful swells that are primarily important in shaping the California coast. However, locally generated seas and wind waves were not included. These “local seas” can be significant contributors to erosion and flooding, and their omission may result in under-estimation of hazards in some areas. Several other physical processes were also not included owing to the additional computational effort and generally lesser importance: wave reflection, diffraction and current-induced refraction.

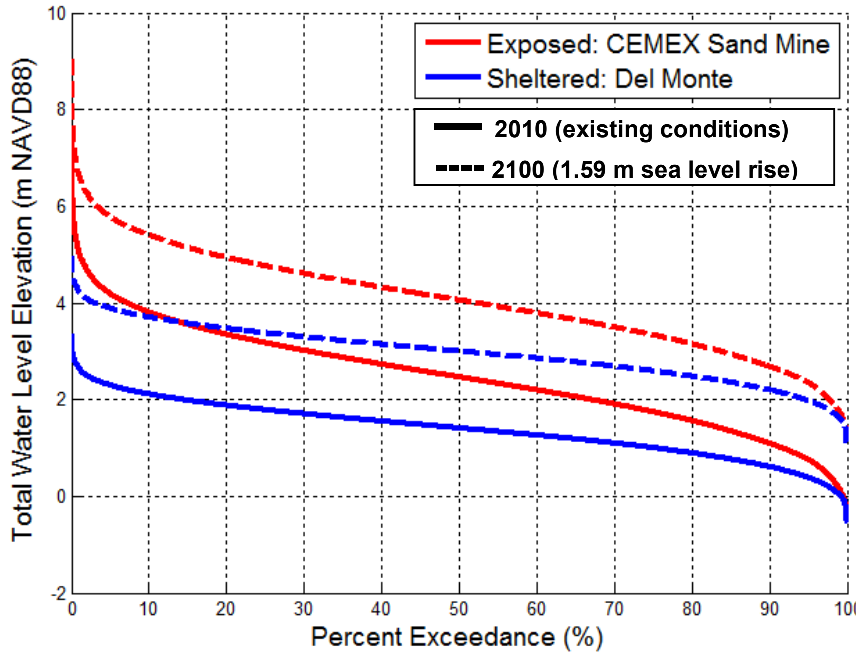
7.2 Wave Runup Calculations and Total Water Level Curves

The total water level is a water elevation determined by the sum of tides, waves and wave runup, and other components including nearshore currents, storm surge, and atmospheric forcing such as El Niño. As sea level rises, the relative amount of time that the water contacts the toe of the dune will increase. This relative increase is the key driving factor forcing this dune erosion model.

For each along-shore study block, the wave runup was calculated using the Stockdon equation (Stockdon et al 2006) with the median beach slope for the block and the time series of wave height and period developed at the nearest of the 44 nearshore wave transformation points. Wave runup was added to the historic tide water levels from the Monterey Bay tide gage (NOAA #94042) from 1996 to 2013 to produce a total water level time series for each block.

Future sea level rise was added to the total water level incrementally at each 10-year time step, with the magnitude depending on which of the three sea level rise scenarios was being modeled (Figure 7). The time series of total water levels for each block and scenario was converted to a total water level exceedance curve, which shows the relative amount of time that wave runup reaches a certain elevation. These curves are the key input to the dune erosion model discussed in the following section. An example of total water level exceedance curves for an exposed (high total water level) and sheltered (low total water level) location is presented in Figure 11, below.

Figure 11 - Example of Total Water Level Curves at Del Monte and CEMEX



8. COASTAL EROSION HAZARD ZONES

8.1 Dune Erosion Methods

Shoreline erosion hazard zones were developed using the methodology described in the Pacific Institute study, with the backshore characterization as the main input (see Section 6). The most important variables in this model are the backshore toe elevation and the total water level curve. This section gives a brief description of the erosion hazard zone methods. For more details about the methods please see the complete Pacific Institute study (PWA 2009 and Revell et al 2011).

Types of Dune Erosion Hazard Zones

Two types of coastal erosion hazard zones were prepared for this study. While not originally scoped, this separation was requested by the TAG to further delineate long term SLR induced changes from storm induced changes.

1. **Long-Term Erosion.** This can be interpreted as the potential future location of the dune crest. Not all areas within the hazard zone are expected to erode to this extent by the specified planning horizon, but any location has the potential to erode to this extent (for the scenario specified). This type of coastal erosion hazard zone is the sum of two components: historic erosion and additional erosion due to sea level rise. The historic erosion rate is applied by the planning horizon to get the baseline erosion, which is an indirect means to account for the sediment budget. The shoreline retreat from sea level rise is calculated by multiplying the increase in run-up above the toe elevation by the overall profile slope (between the backshore toe and the depth of closure).

The potential erosion model ignores the effect of coastal armoring at mitigating erosion. However, if shoreline armoring has been present and maintained over a number of years its presence will be reflected in the calculated historic erosion rates. Additionally, the model does not account for other shore management actions such as sand placement to mitigate future shore recession. In this region, where beaches are controlled in part by dredge placements, we assumed that there were no changes to existing dredge management practices.

2. **100-Year Storm Erosion.** This type of erosion hazard zone adds the erosion caused by a 100-year storm event to the long-term zone described above. The potential inland shoreline retreat caused by the impact from a large storm event (100-year) was estimated using the geometric model of dune erosion originally proposed by Komar et al (1999) and applied with different slopes to make the model more applicable to sea level rise (Revell et al 2011). This method is consistent with the FEMA Pacific Coast Flood Guidelines (FEMA 2005). All potential erosion distances were calculated relative to 2010. These estimates were compared with storm recession observed during the 1997-1998 and 2009 – 2010 El Niño events (Quan, 2011). The erosion estimated in this study was typically higher than those observed in the El Nino events. This is because the "potential erosion" calculated in this study accounts for uncertainty in the duration of a future storm. Instead of predicting storm specific characteristics and response, this potential erosion projection assumes that the coast would erode or retreat to a maximum storm wave event with unlimited duration.

Future Dune Erosion Scenarios

Three future dune erosion scenarios were assessed in this study, as follows:

1. **Continuation of existing wave climate and management** – Assume the wave climate through 2100 remains consistent with the last 17 year record. Also assume a continuation of existing sand mining operations in Monterey Bay. This scenario still considers sea level rise, but does not increase or decrease erosion based solely on wave climate.

2. **Increased storminess** – Assume that the intensity of extreme storms (and the associated extreme wave events) will increase. This is depicted in the erosion hazard zones by including a second 100-year storm in the coastal erosion hazard zones (both the "long-term" and the "with 100-year storm" zones).

3. **Cessation of sand mining** – This management scenario was the highest priority identified in the Coastal Regional Sediment Management Plan. Sand mining in Southern Monterey Bay is the largest sediment deficit in the sediment budget and removes sand from the beach and littoral cell, accelerating erosion. The CEMEX sand mine in Marina has been removing approximately 200,000 cubic yards of sand per year over the past 60 years. A recent study (Thornton 2006, ESA PWA 2012b with Ed Thornton) estimated that cessation of sand mining from the beach would likely reduce erosion rates in Southern Monterey Bay (from the Pajaro River south) by approximately 60-70%. In this analysis, the historic erosion rates were reduced by 60% from the Pajaro River mouth to Wharf II to assess this scenario. As modeled, this scenario does not affect the erosion hazard zones north of the Salinas River.

8.2 Dune Erosion Mapping

The dune erosion hazard zones were mapped for each type of hazard zone (long-term and with 100-year storm), sea level rise scenario, planning horizon, and future erosion scenario using a one-sided buffer in ESRI's ArcGIS software with an ArcINFO® license. The reference line for the erosion hazard zone is the location of the toe of the dune at the time of the statewide LIDAR data collection. The hazard zone also includes the area from the arbitrary offshore baseline to the reference line, as this area (typically the beach) is already in the active erosive coastal zone. Resulting hazard zones were visually inspected and edited for anomalies (e.g. where the angle of the reference line causes the edge of a dune hazard zone to intersect a cliff). The hazard zones thus represent the inland retreat of the dune crest.

8.3 Cliff Erosion Methods

Long-Term Erosion

The Pacific Institute study (PWA 2009 and Revell et al 2011) estimated future erosion rates using the following equation,

$$Erosion\ Rate_{future}(t) = Erosion\ Rate_{historic} * \left(1 + \alpha \frac{P_f - P_e}{P_e}\right)$$

where Pf and Pe are the future and existing probability of total water level exceedance above the cliff toe elevation, respectively. Since the Pacific Institute study, a number of studies have proposed additional relationships for estimating cliff/bluff erosion rates under accelerated sea level rise (Walkden and Dickson 2008, Ashton et al 2011). Walkden and Dickson (2008) found that the following equation applied well for the cliff backed/low volume beaches undergoing a historic trend in sea level rise at the Naze Peninsula on the Essex coast in Southern England:

$$Erosion\ Rate_{future}(t) = Erosion\ Rate_{historic} * \left(\frac{Rate\ of\ Sea\ Level\ Rise\ (t)}{Rate\ of\ Sea\ Level\ Rise\ (historic)}\right)^m$$

In this equation m =0.5. Ashton et al 2011 investigated the value of m using various data sets for calibration and confirmed that m = 0.5 applies to cliffs/bluffs dominated by wave-driven erosion. In particular, rocky shore platforms and cliffs fronted by low-sediment-volume beaches, both of which apply for the cliffs of Northern Santa Cruz.

For this study, Walkden and Dickson 2008 equation was modified, as follows:

$$Erosion\ Rate_{future}(t) = Erosion\ Rate_{historic} * \left(\frac{A\ (t)}{A\ (historic)}\right)^m$$

Where A is the area below the total water level exceedance curve and above the existing toe elevation (Figure 12). This area is a combination of the duration of wave impact above the toe elevation and the intensity of that contact (how high above the toe the waves and wave runup are reaching). The exponent, m, was kept at 0.5, in agreement with the previous studies.

The future erosion rates were integrated through time to obtain an erosion distance at each of the planning horizons. To account for a factor of safety and include a potential failure, a minimum erosion distance of 5 meters was set for all study blocks, which is based on field observations for the respective geological units. The intent was to also address the risk of localized block failures that would not be captured by long-term average erosion, especially in the near term.

Short-Term Variability

There is considerable uncertainty in historic cliff erosion rates due to limited data availability, data resolution, georectification errors, and many other factors. Additionally, the alongshore variability in erosion rates is high, with some locations showing much higher erosion rates than others in nearby locations over the time period sampled. In order to address this variability and uncertainty, two standard deviations of the historic erosion rates within each geologic unit (see Section 4.4) were multiplied by years elapsed to each planning horizon and added to the long-term erosion distances described above. These two standard deviations provide a 95% probability that the current erosion rates are represented.

Future Cliff Erosion Scenarios

Two future cliff erosion scenarios were assessed in this study, as follows:

1. **Continuation of existing conditions** – Assume the wave climate through 2100 remains consistent with the last 17 year record. This scenario still considers sea level rise, but does not increase or decrease erosion based solely on wave climate.

2. **Increased storminess** – Assume that the intensity of extreme storms (and the associated extreme wave events) will increase. This is depicted in the cliff erosion hazard zones by including an additional standard deviation in the alongshore erosion rates, multiplied by time elapsed (as described above). The third standard deviation was included in this scenario to provide additional statistical confidence (99.7%) that the historic rates of erosion are represented and adds an additional safety buffer to this increased storminess scenario.

8.4 Cliff Erosion Mapping

The cliff erosion hazard zones were mapped for each sea level rise scenario, planning horizon, and future erosion scenario using a one-sided buffer in ESRI's ArcGIS software with an ArcINFO® license. The reference line for the erosion hazard zone is the edge of the cliff, which was digitized from recent LiDAR. The hazard zone also includes the beach area shoreward of the cliffs, as this area is already in the active erosive coastal zone. Resulting hazard zones were visually inspected, compared with the Pacific Institute results and edited for anomalies.

9. COASTAL FLOOD HAZARD ZONES

Two types of coastal flood zones were developed for this study: regular flooding by high tides (Section 9.1, once per month, on average) and major flooding caused by a large coastal storm, which would induce wave overtopping and coastal flooding (Section 9.2).

9.1 Rising Tides Inundation Zones

The "rising tides" hazard zone shows which areas will be regularly flooded (once per month, on average) by high tides under future sea level rise (not considering storm events). Two types of rising tide datasets were developed: a general inundation area and a depth grid (or raster). These hazard areas do not consider future erosion, so the coastal erosion hazard zones should be used in combination with these rising tides inundation zones for any applications in the planning process.

Mapping monthly inundation areas

The monthly Extreme Monthly High Water (EMHW) was estimated by averaging the maximum monthly water level for every month recorded at the Monterey Bay tide gage (EMHW = 2.0 meters (6ft 6 inches) NAVD88). In reality, EMHW varies along the coast, especially in the inlets and sloughs. For this project, which is focused on the open coast, a single value of EMHW was used. Sea level rise projections were added to the EMHW for each sea level rise and planning horizon (Section 4.1) and mapped over the 2009 – 2011 CA Coastal Conservancy DEM (Section 4.3). Areas in the DEM below the flood elevation were marked as “flooded.” Then, flooded areas that were connected to the ocean through overland flow were selected, as well as any pools within 5 meters of areas connected to the ocean (the resolution of the depth maps, below) to conservatively account for seepage and potential errors in the DEM[5]. These areas are labeled “connected to ocean over topography” in the “Connection” attribute. The other low-lying areas were also included and were labeled “connection uncertain”[6]. The connectivity of these areas should be assessed for individual sites in the planning process to determine whether they are connected to the ocean (e.g. through culverts, under bridges, etc.).This method is similar to the “low lying areas” in the NOAA SLR viewer. Gaps smaller than 1 acre were assumed flooded, and isolated pools less than 3 m^2 were omitted.

Mapping depth within monthly inundation areas

Depth maps (separate datasets for the “connected” and “connectivity uncertain” maps) were developed by overlaying the monthly inundation area over the topography and using the difference between the flood elevation and the topography to calculate depth. The 2009-2011 CA Coastal Conservancy DEM is hydroflattened, which means that the reported elevations in wet areas correspond to an approximate water surface elevation rather than the actual bathymetry. These areas (as identified by the 3D breaklines provided with the DEM) were assigned a value of 999. This value was specified because depth could not be calculated in these areas (as the LiDAR does not penetrate water). These areas are considered already hazardous as they are already inundated.

9.2 Coastal Storm Flood Hazard Zones

Flooding along the coast is driven by various processes, with the dominant process (likely to cause the most flooding) varying by location and geomorphology. Most sea level rise analyses and maps focus on ocean-tide related flooding (e.g. how a 100-year ocean water level will change with sea level rise). While this may be the dominant process in many sheltered, open-tidal systems, this simplistic approach ignores many of the dominant processes in the Monterey Bay study area. For this study, the shoreline was broken into regions based on the geomorphology and dominant process driving coastal flood levels (Figure 13). The following flood processes were considered:

- 100-year Tide
- Wave Run-up
- Overtopping
- Berm Crest
- Other (including a combination of the above processes)

The subsequent sections describe how these processes were analyzed and mapped for this study. The

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[5] For comparison, the Pacific Institute included areas within 50 meters of a flooded area to account for the coarser DEM used in that analysis.

[6] This is similar to the NOAA SLR Viewer, which maps areas as “low lying” but not flooded.

last section describing how these maps were then combined with the effects of coastal erosion on flooding to create the final coastal storm flood hazard zones.

The major processes that have not been considered are (1) flooding from large precipitation events and (2) river run-off. When combined with high tides and sea level rise at the coastal confluences, these processes likely dominate flooding along the major creeks and rivers in the study area, particularly in the urbanized watersheds (Soquel Creek, San Lorenzo River, Pajaro River, Aptos Creek, and the Salinas River).

100-year Tide

The 100-year tide water level (2.48 m NAVD88, Table 3) was assumed to be the major coastal flood process in predominantly open tidal systems (Figure 13, e.g. Elkhorn Slough, Santa Cruz Harbor). Between Santa Cruz Harbor and Capitola, along the north side of Monterey Bay, the 100-year water level was elevated by 1' using professional judgment to account for wind and wave set-up. These factors are known to increase flood risk to the south facing end of the bay, but are not recorded at the north facing Monterey tide gage (Figure 1). With the previous exception, no variations in extreme water levels were considered (no tidal muting or amplification). As with the rising tides zones, the 100-year water level was raised by sea level rise for future planning horizons.

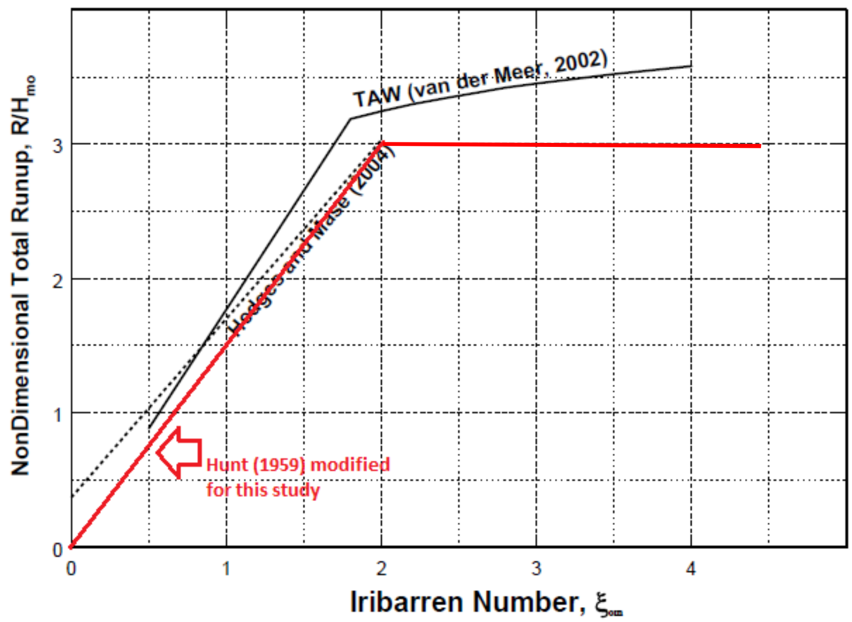
Wave Run-up

The wave run-up elevation typically exceeds that of the 100-year tide water level and the lateral extent of flooding is therefore greater in a number of locations. In these areas (Figure 13), a wave run-up analysis was conducted to estimate the limit of wave runup on the profile. This wave run-up analysis was also used as input to the overtopping analysis, as will be discussed in the next section.

45 representative profiles were analyzed along the entire Monterey Bay study area (Figure 9). The profiles are based on the topography and bathymetry datasets described in Section 4.3. No topography data was available in the surf zone, so the profile was linearly interpolated between the bathymetry and topography limits. They reflect the wide range in topography and bathymetry across the Monterey Bay study area.

The Stockdon runup method (Stockdon et al 2006), which is a fast and simple way to calculate run-up on natural gentle sloping beaches, was used to identify the wave event that caused the maximum runup over the 17-year period of record at every study block. These wave parameters (significant wave height, wave length, direction) were then used as inputs to a runup program that is valid for a wider range of profile configurations (Stockdon 2006 was developed for wide natural beaches). A run-up program developed by ESA PWA and consistent with FEMA guidelines was used to iteratively calculate the dynamic water surface profile along each representative profile, the nearshore depth-limited wave, and the run-up elevation at the end of the profile. The dynamic water surface is the water level right at the coast that is driven by sets of waves (or wave groups) that cause superelevation of these water levels Wave run-up is computed using the method of Hunt (1959) which is based on the Irribarren number (also called the Surf Similarity Parameter), a non-dimensional ratio of shore steepness relative to wave steepness. The run-up is limited to a maximum of about three times the incident wave height, which is generally consistent with other methods that rely on the relative steepness parameter, as depicted in Figure 14. While there are a variety of run-up equations, they provide a range of results and hence the most simple and direct was chosen (Hunt, 1959).

Figure 14 - Non-dimensional Total Runup vs. Iribarren Number



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Wave runup relative to wave height is modeled as being proportional to the Iribarren Number, also known as the Surf Similarity Parameter, which is the ratio of the beach slope to the square root of wave steepness (relative slope steepness). Note that the wave runup is limited above a value of three times the incident wave height. (Source: FEMA 2005).

The program also uses the Direct Integration Method (DIM) to estimate the static and dynamic wave setup and resulting water surface profile (FEMA 2005; Dean and Bender 2006; Stockdon 2006). The methodology is consistent with the FEMA Guidelines for Pacific Coastal Flood Studies for barrier shores, where wave setup from larger waves breaking farther offshore, and wave runup directly on barriers combine to form the highest total water level and define the flood risk (FEMA 2005). This program also incorporates surface roughness of the structure and overland which acts as friction on the uprush of the waves thus reducing the extent of wave runup. This method also uses a composite slope technique as outlined in the Shore Protection Manual (USACE 1984) and Coastal Engineering Manual (USACE 2002).

The wave run-up elevation was mapped over the LiDAR topography to develop the flood hazard map for the regions where wave run-up was identified as the dominant flood hazard (Figure 13).

Overtopping

This method was used in placed where low-lying areas are separated (disconnected) from the ocean by dunes, coastal armoring structures, or other obstructions. During large wave events, wave run-up can overtop these structure and flow into back-barrier low-lying areas. Because these areas are disconnected from the ocean, flood waters cannot easily drain, causing persistent flooding. ESA PWA is unaware of any other sea level rise vulnerability studies consider this flooding process. This study developed an innovative approach, consistent with FEMA guidelines, to assess flooding from overtopping and estimate how it will change in the future with coastal erosion and sea level rise. Limited data were available to calibrate the model, but anecdotal observations of flooding in Capitola and the City of Monterey were taken into account. Figure 13 shows the regions where wave overtopping was determined to be the dominant flood hazard.

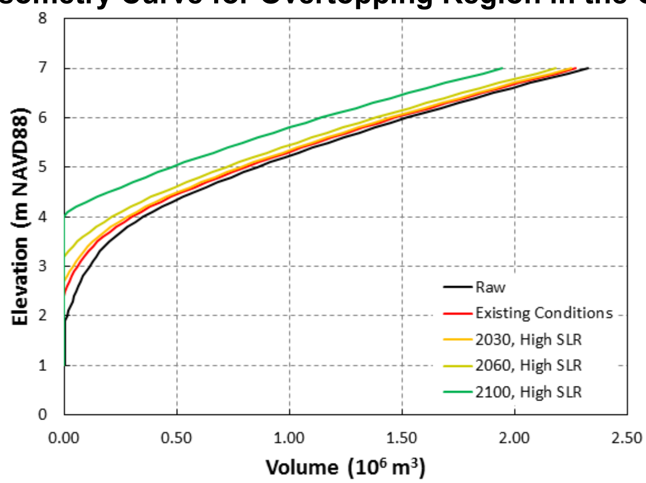
Flood extents from wave overtopping were assessed as follows:

1. Delineate flood basins (low-lying areas that would fill with water from wave overtopping).

2. Calculate existing hypsometry curves[7] using the Surface Volume tool in ArcGIS. Figure 15 shows an example of the existing conditions hypsometry curve. Appendix 5 describes how the hypsometry was modified for each region.

3. Develop future hypsometry curves. With sea level rise, the water level in low lying areas may rise due to higher groundwater levels or connections through underground culverts. The future curves (2030, 2060, and 2100) reflect this assumed rise in the groundwater levels corresponding to the projected change in sea level rise.

Figure 15 – Hypsometry Curve for Overtopping Region in the City of Monterey



4. Using the dune erosion hazard zones (no change to sand management or storm frequency, with 100-year storm), estimate the future dune crest elevations. Locate the dune crest along each detailed topographic profile (Figure 16, red lines) and identify the future crest elevation by intersecting the limit of the hazard zone with the profile. Appendix 5 describes in further detail the assumptions made about future crest elevations in each region.

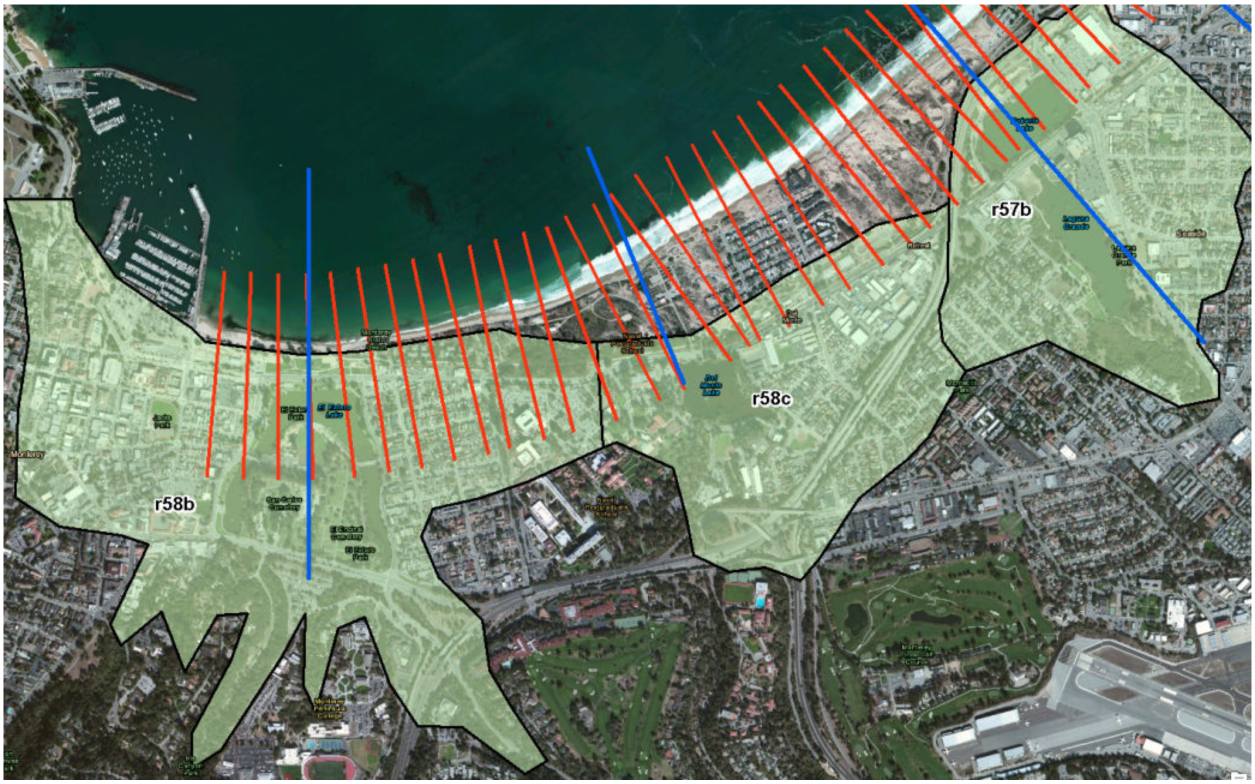
5. Generate a look-up table of overtopping volumes (m^3/m of shore/m of freeboard) for each flood analysis profile (Figure 16, blue lines) that intercepts an overtopping region. Assume a 4 hour storm (limited by duration of high tide) event with representative wave conditions (described above in Section 7). This step enables the volume of a single wave overtopping to be converted to a flow volume. The overtopping calculations are described in detail in Appendix 6.

6. Calculate the total overtopping volume for each detailed profile (Figure 16, red lines) to capture the variability in crest elevations along shore. Calculate the height of water above the structure (e.g. the negative freeboard) for each profile by subtracting the crest elevation (a function of time) from the wave run-up elevation (see “Wave Runup” section above) and adding sea level rise (also a function of time). Assign an along-shore distance to each detailed profile (usually 100 m) and use the lookup table described in the previous step to estimate the total overtopping volume (m^3) flowing into the region over each profile.

[7] Hypsometry, in this case, refers to the relationship between a water surface elevation and volume of water stored in the flood basin when the water is at that elevation. A hypsometry curve shows the volume for a wide range of water surface elevations.

7. Sum the volumes over all the detailed profiles to estimate total volume flowing into each region, and use the hypsometry curves (described in steps 2 and 3) to convert the volume to a water surface elevation. Some judgment was used to set a maximum and minimum flood elevation for each region, as described in Appendix 5. Map the flood elevation over the existing topography.

Figure 16 – Example of Flood Analysis Transects and Regions for Overtopping



Seasonally Closed Lagoons (Bar Built Estuaries)

The Monterey Bay shoreline (and much of the California coast) is punctuated by coastal lagoon systems, which occur at confluences between creeks/rivers and the ocean. These systems are seasonally controlled by opposing forces: (1) waves that build up the sandy beach, causing the lagoon to close (usually in the summer/fall) and fill with water behind the beach and (2) rainfall runoff that encourages the lagoon to breach and flow into the ocean through a channel. Unlike open tidal systems, these seasonally closed lagoons often experience the highest water levels during closed conditions, when a high beach berm develops and there is enough runoff to fill the lagoon but not breach. This is complicated by management activity (e.g. mechanical or artificial breaching), which varies greatly between lagoons. For this study, a number of seasonally closed lagoons were identified along the Monterey Bay shoreline (Figure 13). These were geomorphically interpreted based on sediment grain size characteristics, beach slopes, and wave exposure. By using the spring 1998 and fall 2010 LiDAR combined with site observations and professional judgment, ESA PWA estimated a maximum potential beach berm elevation which would back up the lagoon waters and cause the highest flooding levels. It was then assumed that the maximum flood level would occur when the lagoon filled up to the beach berm just before spilling over and breaching (naturally), which is typical during rainfall events. These water levels are not associated with a particular return interval (e.g. 100-year) – this would require understanding the joint probability of waves building up the beach with the timing/magnitude/probability of large rainfall events, which is beyond the scope of this project.

Table 6. Assumed Maximum Berm Crest Elevations for Seasonally Closed Lagoons

Lagoon Name	"Maximum" Berm Crest *ft NAVD88*
Waddell Creek	15
Scott Creek	16
Laguna Creek	16
Majors Creek	14
4-Mile	14
3-Mile	14
Old Dairy Gulch	14
Wilder Creek	14
North Natural Bridges	14
Natural Bridges	14
Corcoran Lagoon	12
Pajaro River	16
Salinas River	16

In the future, the sediment supply is assumed to be consistent with existing conditions to allow the "maximum beach berm elevation" to rise in equilibrium with sea level (i.e. the maximum flood elevation in the closed lagoon rises at the same rate as sea level). The existing and future maximum flood elevations were mapped over existing topography to identify the flood hazard zone in these seasonally closed lagoons systems.

Other

In two locations (Twin Lakes and Moran Lake), a road crosses low to the beach and all lagoon flow goes through a small culvert, which is sometimes blocked during the natural onshore offshore cycle of sand movement in the nearshore surf zone. Naturally, these locations would likely function as seasonally closed lagoons. However, the road blocks most flow exchange between the ocean and lagoon. Therefore, rather than estimate a maximum possible berm crest elevation, the road crest was selected as the maximum flood level. This is likely a conservative estimate as inflow would be limited by time and some return flow could leave the lagoon through the culvert. However, unlike the beach berms, the road crest will not rise with sea level rise. Therefore, the maximum flood level in these two lagoons was set at the road crest elevation or the 100-year tide level (which rises with sea level rise), whichever one was higher.

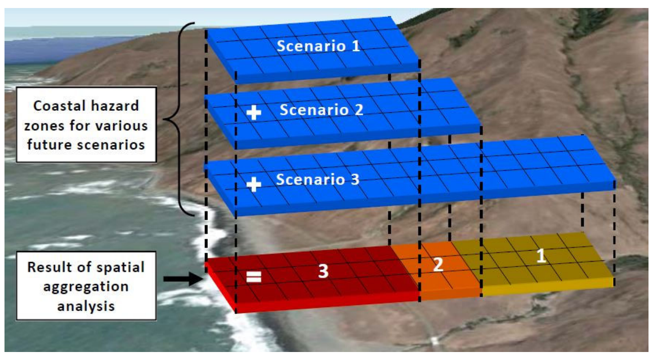
Mapping Coastal Storm Flood Hazard Zones

The individually mapped regions, described in the previous sections, were merged with the dune and cliff erosion hazard zones. This merging was to include all areas that become hazardous due to future erosion in the future flood hazard zones. Flooded areas with connectivity to the ocean (over the digital elevation model) were mapped, as well as any pools (greater than 3 m^2) within 5 meters of areas connected to the ocean to conservatively account for seepage and potential errors in the DEM. For the same reason, donut holes smaller than 1 acre are shown as flooded. Areas without apparent connection to the ocean were kept but were labeled as "connectivity uncertain" in the attribute table. These should be displayed in a different shade to show that unless there is a connection (e.g. through a culvert/under a bridge), those areas will not necessarily flood due to coastal processes. Overtopping flood hazard areas are considered "connected" as the modeling results (and in some cases, observations) show that wave run-up can connect those low-lying areas to the ocean.

10. ASSESSING A RANGE OF SCENARIOS

This study considered a range of future scenarios related to sea level rise, storm erosion, sand mining, and storm frequency. A set of simple layers were developed to easily visualize the range of hazard outcomes from all scenarios. At each planning horizon (2030, 2060, 2100), all the hazard zones of a certain type (e.g. dune erosion or coastal storm flooding) were overlaid to identify how "hazardous" a given location is. The level of hazard was quantified by counting the number of scenarios that result in a location being hazardous. For the flood hazard zones (either regular tidal inundation or coastal storm flooding), the three sea level rise scenarios were overlaid. In the case of the coastal erosion hazard zones, all the erosion scenarios are overlaid: three sea level rise scenarios, with and without a 100-year storm, with and without a continuation of sand mining (where applicable), and with and without an increase in storm frequency. This process of overlaying and counting the number of overlapping hazards is called "spatial aggregation," and is shown in Figure 17. An example output for the dune erosion hazard zones in the year 2100 is shown in Figure 6.

Figure 17 – Spatial Aggregation Schematic



These spatially aggregated layers do not, by any means, contain a comprehensive range of possible future scenarios, and none of the scenarios presented are associated with a certain probability of future occurrence (which requires statistical approaches which are exceedingly complex given the large range of uncertainty associated with projections of sea level rise). This is simply a way to visualize the full range of scenarios assessed and understand, qualitatively, how projected future hazards vary (e.g. if a site is hazardous regardless of the scenario, or whether the site is only hazardous for the most extreme scenarios).

11. LIST OF PREPARERS

This report was prepared by Elena Vandebroek, P.E., David Revell, Ph.D. (Project Manager), and To Dang, Ph.D. with technical oversight by Bob Battalio, P.E. (Project Director). Additional support was provided by Dane Behrens, PhD and James Jackson.

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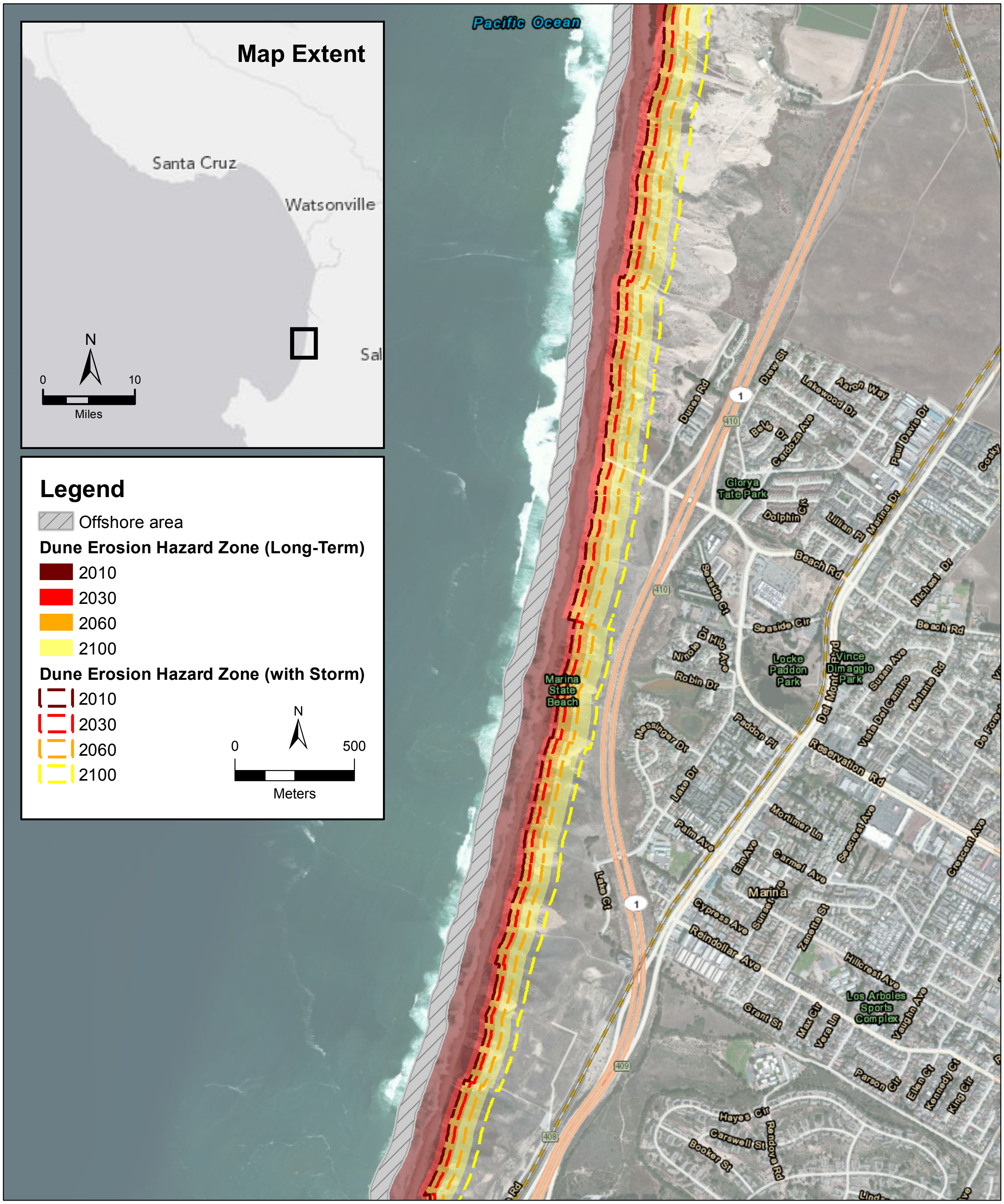
3/4/2014

Monterey Bay Sea Level Rise Assessment . 211906.00

Figure 1
Study Area



Note: The hazards shown are for the "high sea level rise" scenario of 1.59 meters of SLR by 2100, relative to 2010. These hazard zones are for the "continuation of existing wave climate and sand management" scenario.

Monterey Bay Sea Level Rise Assessment . 211906.00

Figure 2

Example of Dune Erosion Hazard Zones

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Note: The hazards shown are for the "high sea level rise" scenario of 1.59 meters of SLR by 2100, relative to 2010. These hazard zones are for the "continuation of existing wave climate" scenario.

Monterey Bay Sea Level Rise Assessment . 211906.00

Figure 3

Example of Cliff Erosion Hazard Zones

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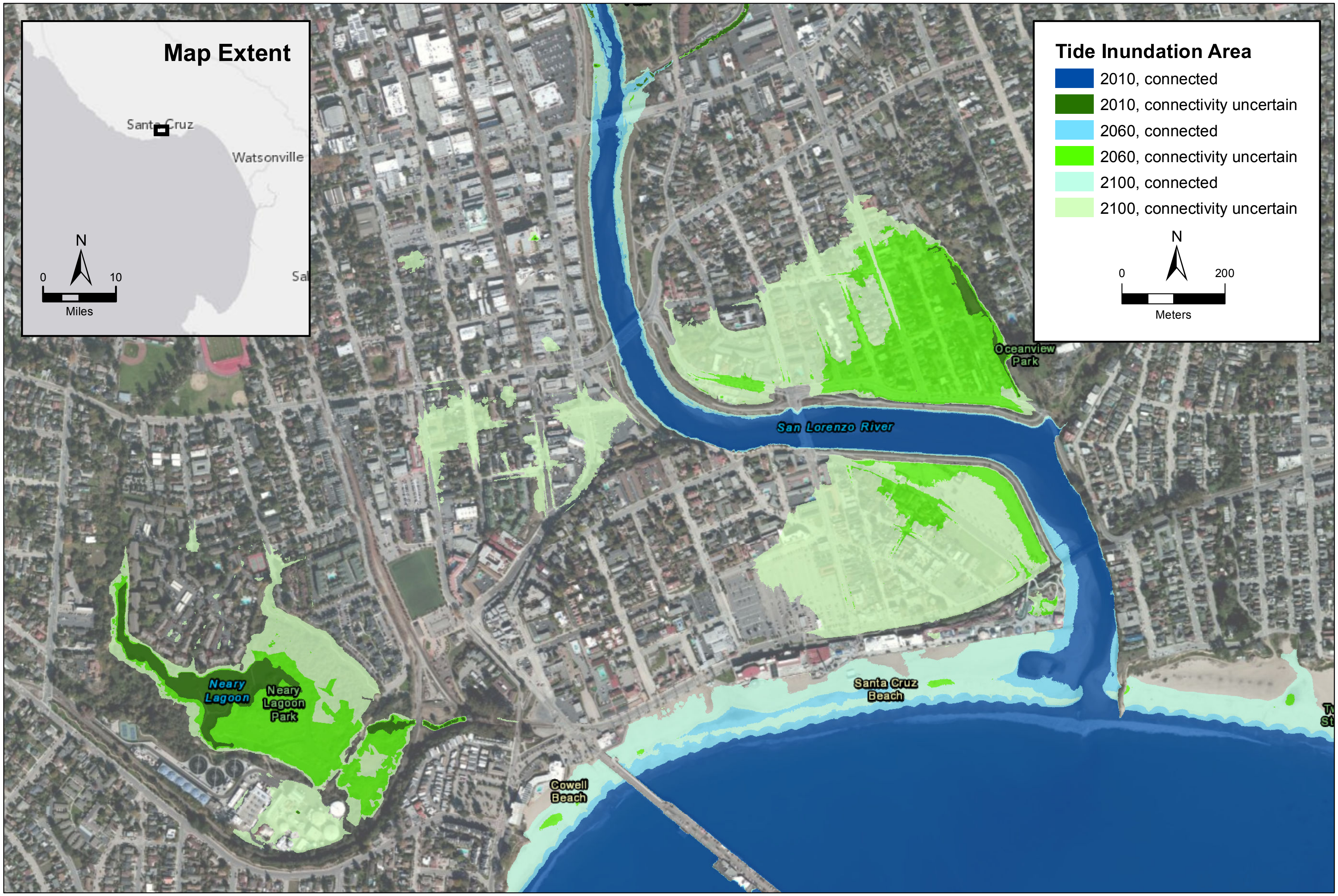
3/4/2014



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Monterey Bay Sea Level Rise Assessment . 211906.00

Figure 4a

Example of Monthly Tide Inundation Area

NOTES:
1. These future tide inundation zones are for the "High" sea level rise scenario of 1.59 meters by 2100, relative to 2010.
2. Assumes a monthly extreme water level of 2.00 m NAVD88 in 2010, as estimated by ESA PWA.
3. This hazard zone does not consider future erosion of the coast and should be used in conjunction with the coastal erosion hazard zones.

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NOTES:
1. These future tide inundation zones are for the "Medium" sea level rise scenario of 0.88 meters by 2100.
2. Assumes a monthly extreme water level of 2.00 m NAVD88 in 2010, as estimated by ESA PWA.
3. This hazard zone does not consider future erosion of the coast and should be used in conjunction with the coastal erosion hazard zones.

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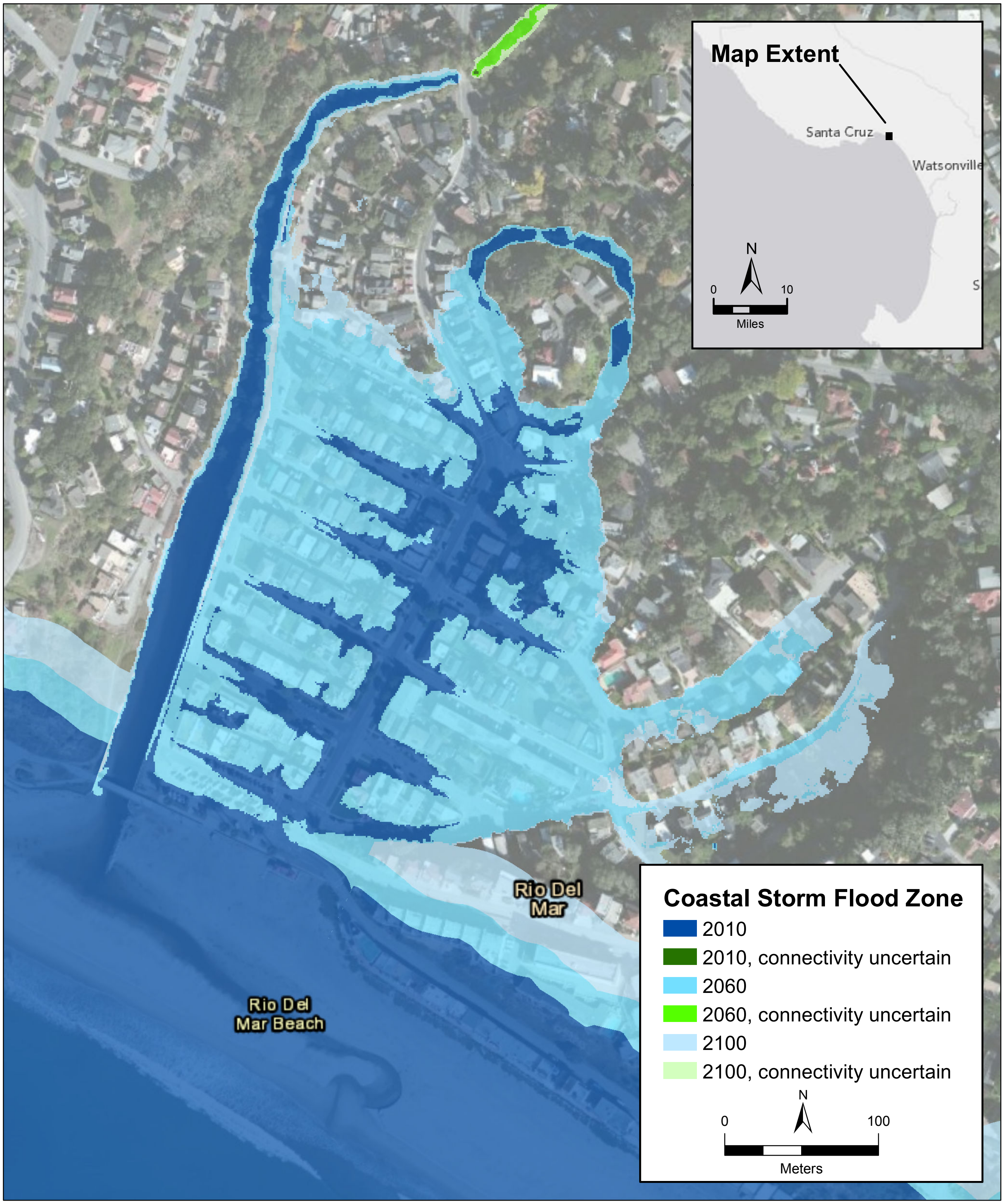
Figure 4b
Example of Monthly Tide Inundation Depth (Year 2060)



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Note: The hazards shown are for the "high sea level rise" scenario of 1.59 meters of SLR by 2100, relative to 2010.

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Figure 5

Example of Coastal Storm Flood Hazard Zones

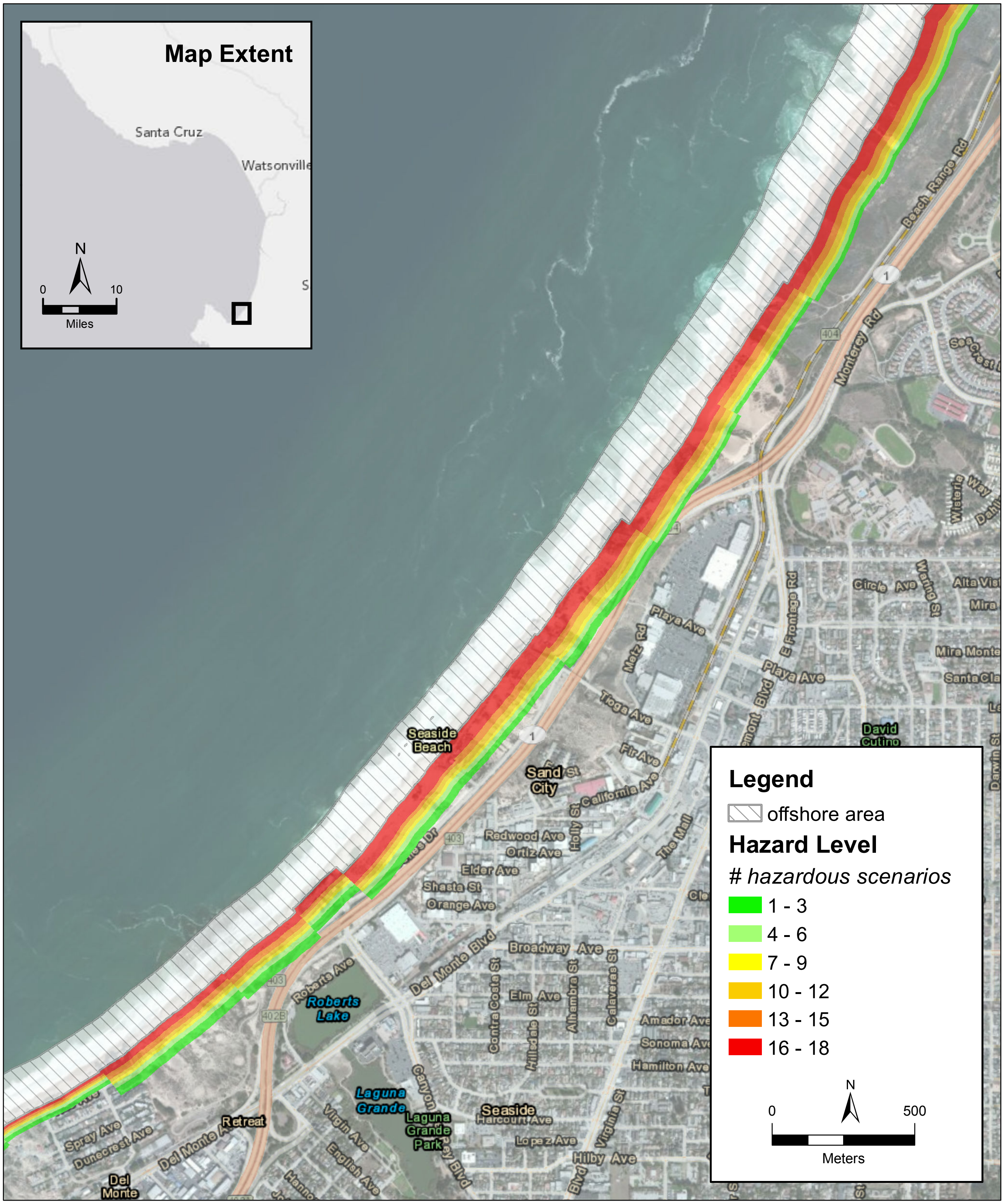

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Figure 6
Example of Spatial Aggregation to Visualize a Range of Scenarios

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Figure 8
Coastal Geology

Figure 9
Wave Transformation Points and Flood Analysis Profiles

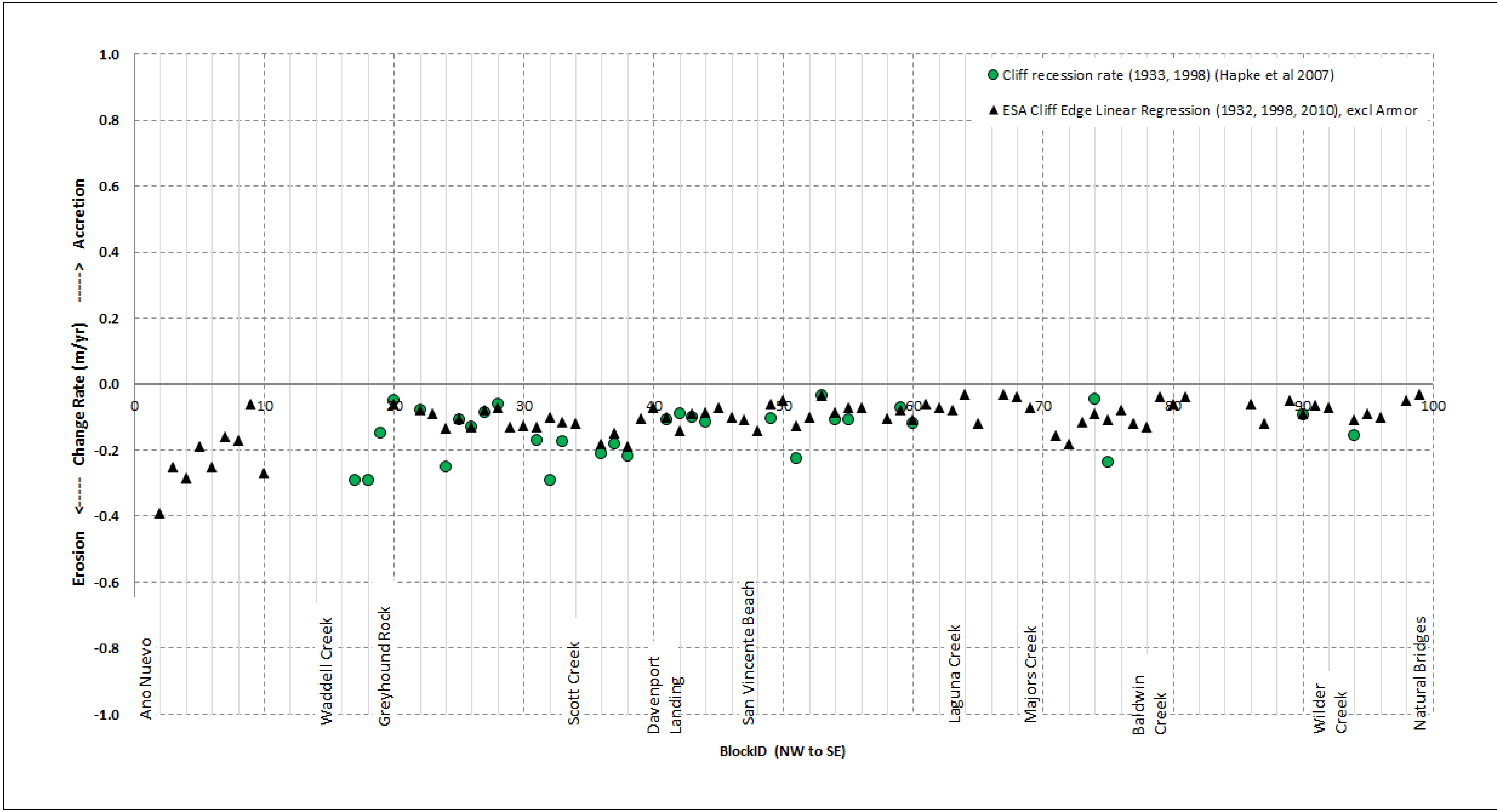


Figure 10a. Historic Erosion Rates in Northern Santa Cruz County

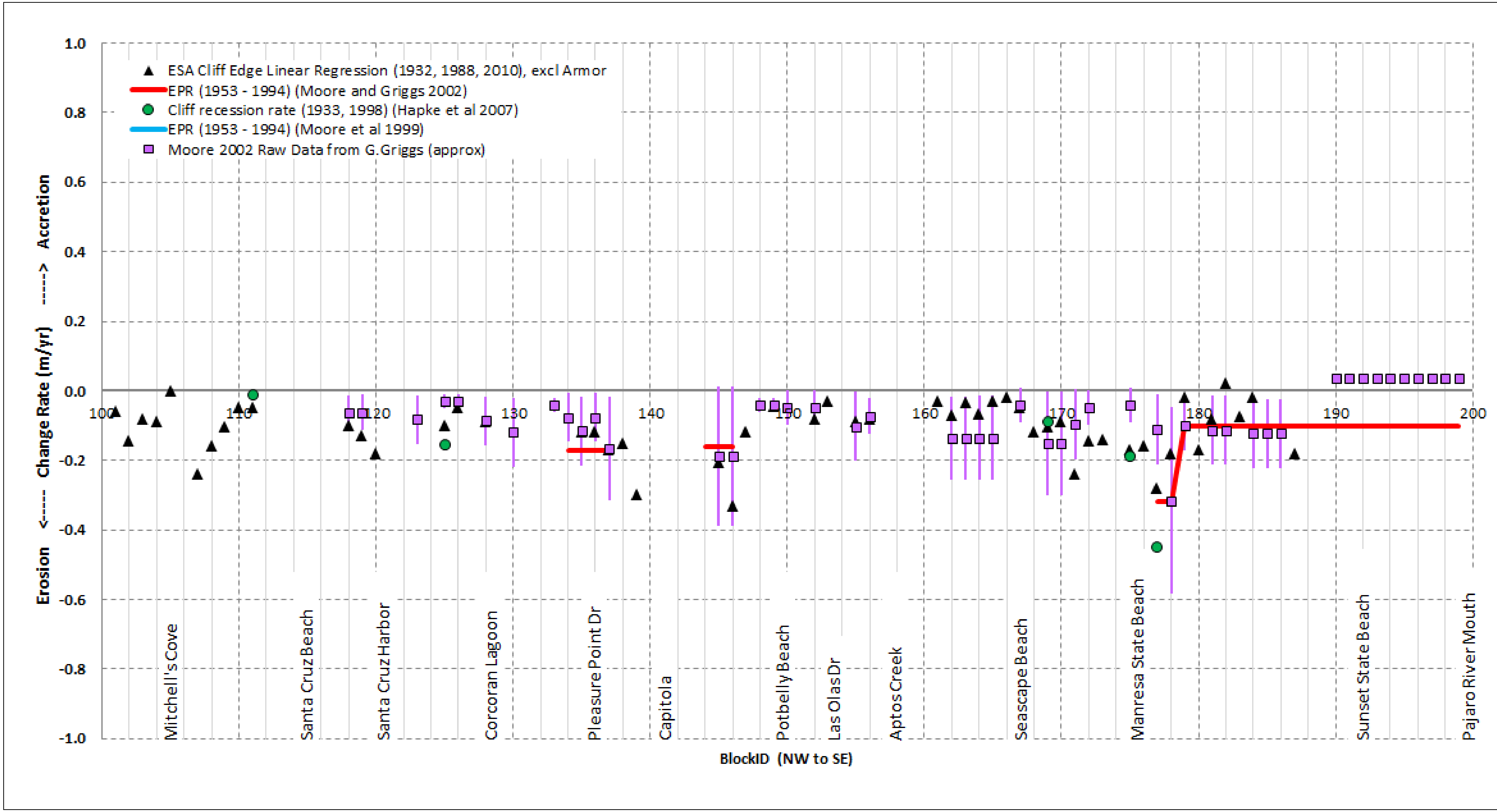


Figure 10b. Historic Erosion Rates in Northern Monterey Bay

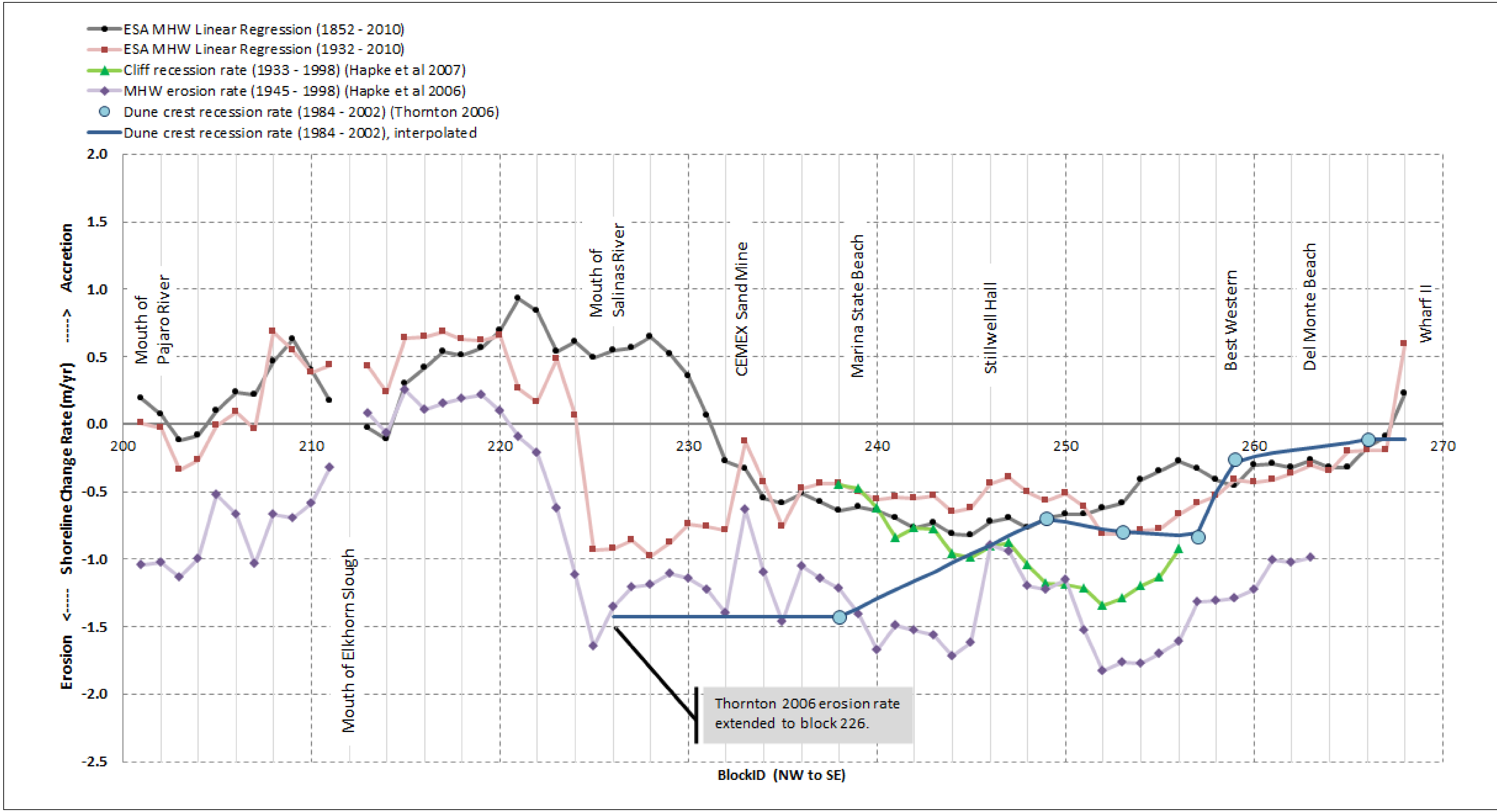
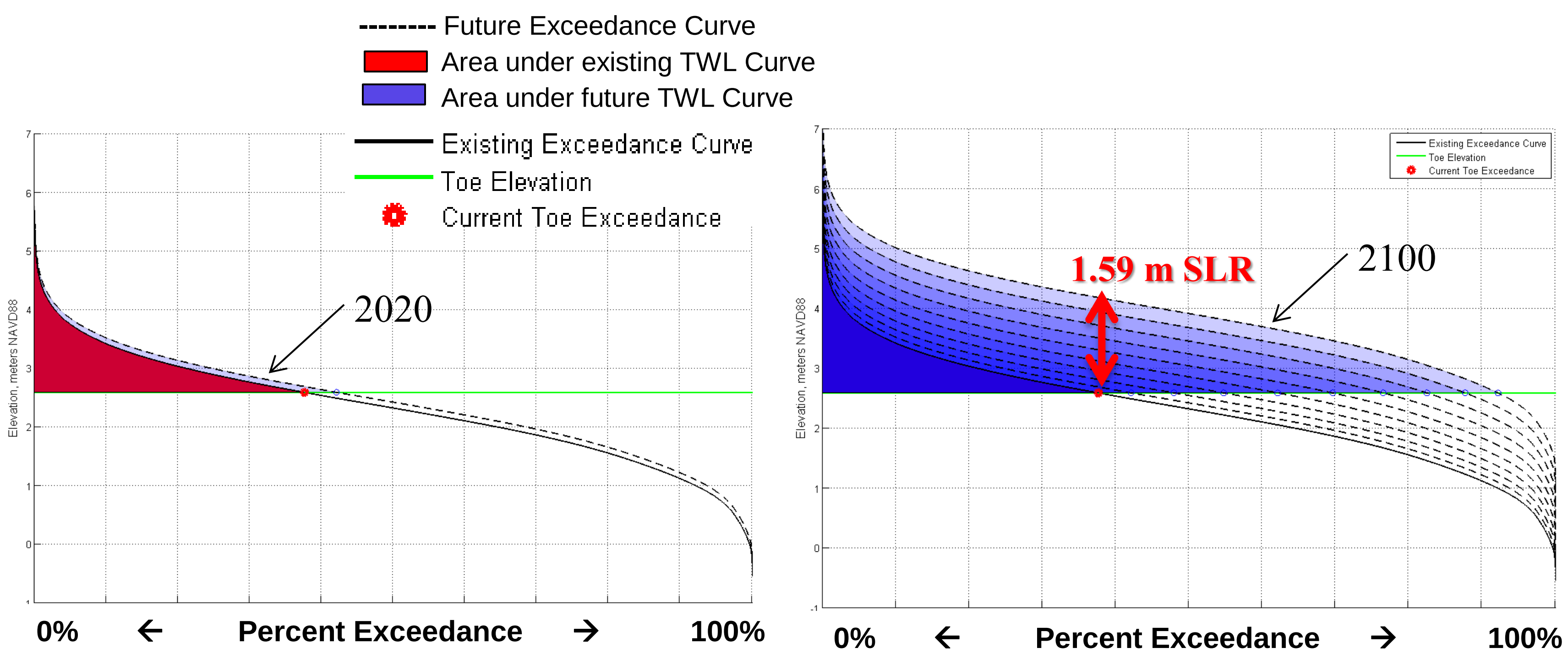
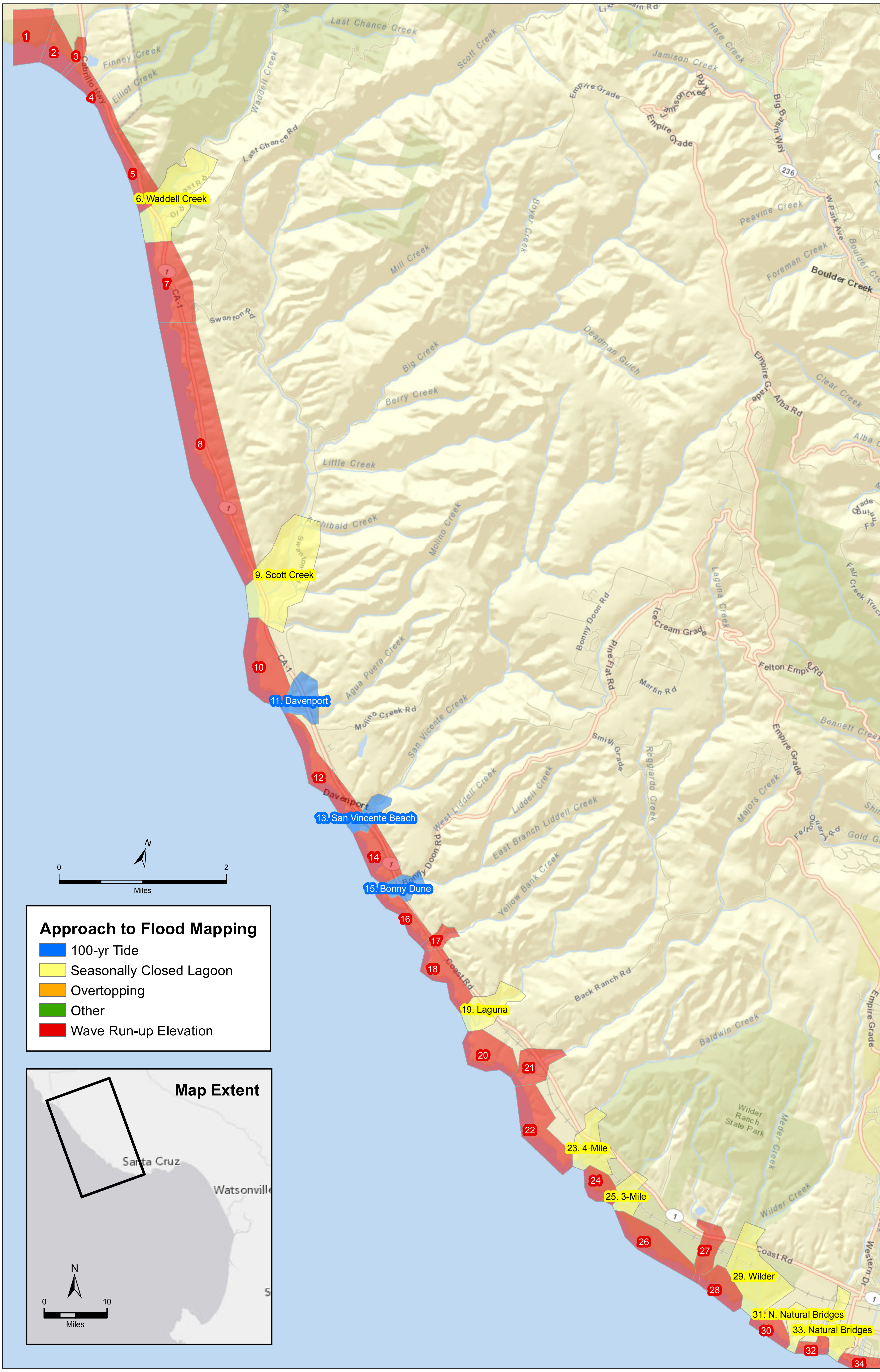


Figure 10c. Historic Erosion Rates in Southern Monterey Bay



SOURCE: ESA PWA

Figure 12
Cliff Erosion Methods



Monterey Bay Sea Level Rise Assessment . 211906.00

Figure 13a

Flood Hazard Mapping Approach, by Region (Northern Santa Cruz County)

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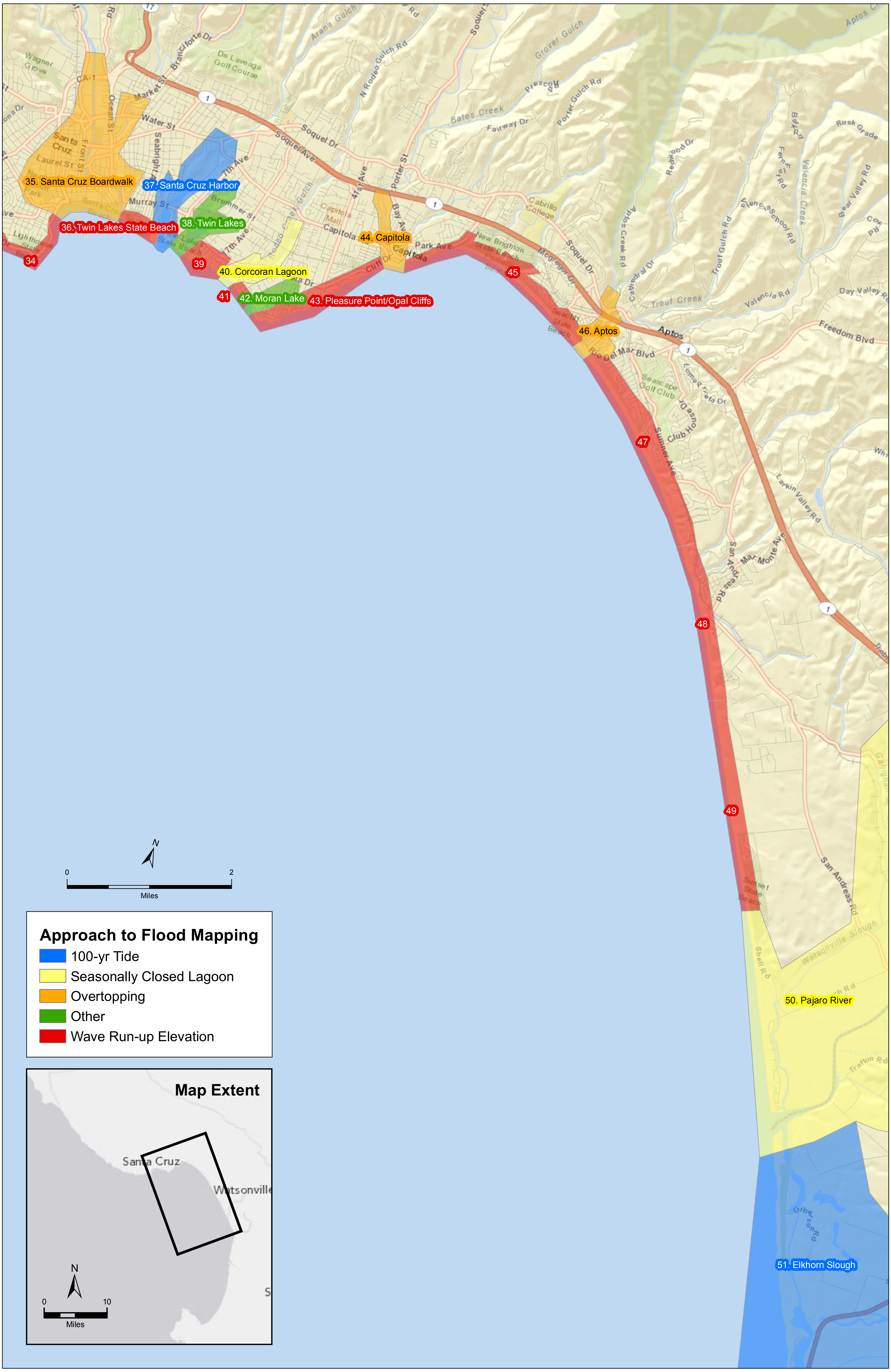

Monterey Bay Sea Level Rise Assessment . 211906.00

Figure 13b

Flood Hazard Mapping Approach, by Region (Northern Monterey Bay)

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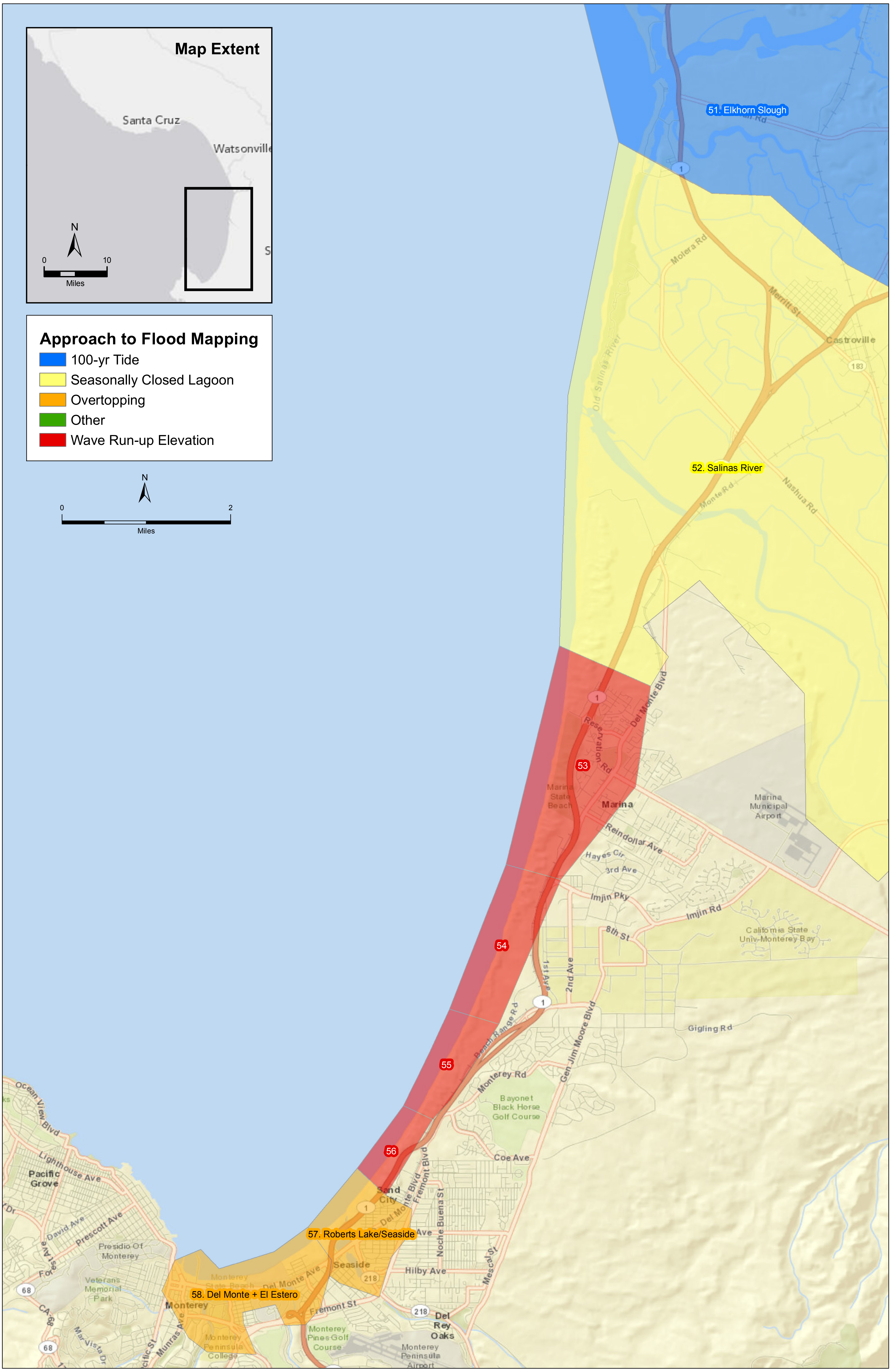

Monterey Bay Sea Level Rise Assessment . 211906.00

Figure 13c

Flood Hazard Mapping Approach, by Region (Southern Monterey Bay)

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2/21/2014

Appendix 1

LIST OF COASTAL HAZARD GIS FILES

Appendix 1. List of Coastal Hazard GIS Files

File Name	Folder	File Type	Hazard Zone Type	Prefix	Spatial Aggr?	Projection Type	Erosion Scenario	Sea Level Rise	Planning Horizon
dune erosion hazard zones									
dhz_longterm_nochange_s12030.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	longterm	nochange	s1	2030
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dhz_longterm_nochange_s12100.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	longterm	nochange	s1	2100
dhz_longterm_nochange_s22030.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	longterm	nochange	s2	2030
dhz_longterm_nochange_s22060.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	longterm	nochange	s2	2060
dhz_longterm_nochange_s22100.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	longterm	nochange	s2	2100
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dhz_longterm_nochange_s32060.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	longterm	nochange	s3	2060
dhz_longterm_nochange_s32100.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	longterm	nochange	s3	2100
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dhz_wstorm_stormier_s12060.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s1	2060
dhz_wstorm_stormier_s12100.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s1	2100
dhz_wstorm_stormier_s22030.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s2	2030

Appendix 1. List of Coastal Hazard GIS Files

File Name	Folder	File Type	Hazard Zone Type	Prefix	Spatial Aggr?	Projection Type	Erosion Scenario	Sea Level Rise	Planning Horizon
dhz_wstorm_stormier_s22060.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s2	2060
dhz_wstorm_stormier_s22100.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s2	2100
dhz_wstorm_stormier_s32030.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s3	2030
dhz_wstorm_stormier_s32060.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s3	2060
dhz_wstorm_stormier_s32100.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	No	wstorm	stormier	s3	2100
dune erosion hazard zones, aggregated									
dhz_aggr_2030.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	Yes	N/A	N/A	N/A	2030
dhz_aggr_2060.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	Yes	N/A	N/A	N/A	2060
dhz_aggr_2100.shp	1_dune_erosion\v14	polygon shapefile	Dune Erosion Hazard Zone	dhz	Yes	N/A	N/A	N/A	2100
cliff erosion hazard zones									
chz_longterm_nochange_s12030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s1	2030
chz_longterm_nochange_s12060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s1	2060
chz_longterm_nochange_s12100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s1	2100
chz_longterm_nochange_s22030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s2	2030
chz_longterm_nochange_s22060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s2	2060
chz_longterm_nochange_s22100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s2	2100
chz_longterm_nochange_s32030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s3	2030
chz_longterm_nochange_s32060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s3	2060
chz_longterm_nochange_s32100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	nochange	s3	2100
chz_longterm_stormier_s12030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s1	2030
chz_longterm_stormier_s12060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s1	2060
chz_longterm_stormier_s12100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s1	2100
chz_longterm_stormier_s22030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s2	2030
chz_longterm_stormier_s22060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s2	2060
chz_longterm_stormier_s22100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s2	2100
chz_longterm_stormier_s32030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s3	2030
chz_longterm_stormier_s32060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s3	2060
chz_longterm_stormier_s32100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	longterm	stormier	s3	2100
chz_wstorm_nochange_ec2010.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	ec	2010
chz_wstorm_nochange_s12030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s1	2030
chz_wstorm_nochange_s12060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s1	2060
chz_wstorm_nochange_s12100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s1	2100
chz_wstorm_nochange_s22030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s2	2030
chz_wstorm_nochange_s22060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s2	2060
chz_wstorm_nochange_s22100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s2	2100
chz_wstorm_nochange_s32030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s3	2030
chz_wstorm_nochange_s32060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s3	2060
chz_wstorm_nochange_s32100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	nochange	s3	2100
chz_wstorm_stormier_ec2010.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	ec	2010
chz_wstorm_stormier_s12030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s1	2030
chz_wstorm_stormier_s12060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s1	2060
chz_wstorm_stormier_s12100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s1	2100
chz_wstorm_stormier_s22030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s2	2030
chz_wstorm_stormier_s22060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s2	2060
chz_wstorm_stormier_s22100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s2	2100
chz_wstorm_stormier_s32030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s3	2030
chz_wstorm_stormier_s32060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s3	2060
chz_wstorm_stormier_s32100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	No	wstorm	stormier	s3	2100
cliff erosion hazard zones, aggregated									
chz_aggr_2030.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	Yes	N/A	N/A	N/A	2030
chz_aggr_2060.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	Yes	N/A	N/A	N/A	2060
chz_aggr_2100.shp	2_cliff_erosion\v08	polygon shapefile	Cliff Erosion Hazard Zone	chz	Yes	N/A	N/A	N/A	2100

Appendix 1. List of Coastal Hazard GIS Files

File Name	Folder	File Type	Hazard Zone Type	Prefix	Spatial Aggr?	Projection Type	Erosion Scenario	Sea Level Rise	Planning Horizon
rising tides inundation zones, area									
tide_area_ec2010.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	ec	2010
tide_area_s12030.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s1	2030
tide_area_s12060.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s1	2060
tide_area_s12100.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s1	2100
tide_area_s22030.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s2	2030
tide_area_s22060.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s2	2060
tide_area_s22100.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s2	2100
tide_area_s32030.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s3	2030
tide_area_s32060.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s3	2060
tide_area_s32100.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	No	N/A	N/A	s3	2100
rising tides inundation zones, aggregated									
tide_area_aggr_2030.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	Yes	N/A	N/A	N/A	2030
tide_area_aggr_2060.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	Yes	N/A	N/A	N/A	2060
tide_area_aggr_2100.shp	3_rising_tides\area	polygon shapefile	Rising Tides Inundation Zone	tide_area	Yes	N/A	N/A	N/A	2100
rising tides inundation zones, depth									
dep_ec2010	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	ec	2010
dep_s12030	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s1	2030
dep_s12060	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s1	2060
dep_s12100	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s1	2100
dep_s22030	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s2	2030
dep_s22060	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s2	2060
dep_s22100	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s2	2100
dep_s32030	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s3	2030
dep_s32060	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s3	2060
dep_s32100	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep	No	N/A	N/A	s3	2100
dep_l_ec2010	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	ec	2010
dep_l_s12030	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s1	2030
dep_l_s12060	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s1	2060
dep_l_s12100	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s1	2100
dep_l_s22030	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s2	2030
dep_l_s22060	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s2	2060
dep_l_s22100	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s2	2100
dep_l_s32030	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s3	2030
dep_l_s32060	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s3	2060
dep_l_s32100	3_rising_tides\depth	raster (5m)	Rising Tides Depth	dep_l	No	N/A	N/A	s3	2100
coastal storm flood hazard zones									
coastal_floodhz_ec2010.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	ec	2010
coastal_floodhz_s12030.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s1	2030
coastal_floodhz_s12060.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s1	2060
coastal_floodhz_s12100.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s1	2100
coastal_floodhz_s22030.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s2	2030
coastal_floodhz_s22060.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s2	2060
coastal_floodhz_s22100.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s2	2100
coastal_floodhz_s32030.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s3	2030
coastal_floodhz_s32060.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s3	2060
coastal_floodhz_s32100.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	No	N/A	N/A	s3	2100
coastal storm flood hazard zones, aggregated									
coastal_floodhz_aggr_2030.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	Yes	N/A	N/A	N/A	2030
coastal_floodhz_aggr_2060.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	Yes	N/A	N/A	N/A	2060
coastal_floodhz_aggr_2100.shp	4_coastal_storm_flood	polygon shapefile	Coastal Storm Flood Hazard Area	coastal_floodhz	Yes	N/A	N/A	N/A	2100

Appendix 2

WAVE REFRACTION IN MONTEREY BAY

By E.B. Thornton

Wave Refraction in Monterey Bay

E.B. Thornton

The wave refraction coefficients for this study were calculated using the linear refraction model by Dobson (1967) modified to refract the rays from a specified shallow water location, back to deep water. This “back” refraction model was developed to obtain refractive information at specific locations. The model searches for the 4 m isobath along a normal to the shoreline that originates at selected points of interest. Rays for frequencies from 0.03 to 0.17 Hz (33.3 to 5.9 sec) are propagated offshore at 0.1 degree increments over the range of all possible arrival angles. These frequencies represent swell waves originating outside the bay. Higher frequencies represent locally generated wind waves. Once in deep water, the rays are stopped and the deep water angle is measured; then the rays are turned around and propagated back inshore along the same path to calculate the spectral refraction coefficient. The rays must return to the initial location within the specified area of $\pm$ 100m to be a valid calculation. Average refraction coefficients are calculated by averaging the calculated values falling in 22.5 degree bands. The center angles of the directional bands were selected to conform to directional spectra generated by the U.S Army WIS and U.S. Navy GSWOM global wave programs. Examples of spectral refraction in Monterey Bay for station 9 are presented in Figure 1.

The bathymetry used in the refraction model is critical to the analysis. The accuracy of the calculated refraction information can be no better than the accuracy of the bathymetry. Consequently considerable effort was devoted to accurately depict the bottom. Original NOAA data was obtained that had been projected onto a six-second modified Universal Transverse Mercator (UTM) grid. The bathymetry data was initially screened for bad points, and then the data was scanned along meridians and parallels for changes in slope that exceeded 30 degrees. Points that generated unrealistic bathymetry were extracted from the data base, and the resultant bathymetry was projected onto an x-y plane via a modified UTM projection. The bathymetry was interpolated to a 200 m rectangular grad using a piecewise-linear, triangular plane interpolator. The triangulation method provides reasonable results in data sparse regions with minimum distortion of bathymetric features. Intermediate smoothing was accomplished using a nine-point, weighted, linear-averaging, and further smoothing was provided by the model itself, which calculates bottom curvature by fitting a quadratic surface to adjacent isobaths. Waves originating from the northerly most quadrant are refracted when travelling over the shoal shelf region between the Farallon Islands and Pont Santa Cruz. To include the refraction to the north, a supplemental northern bathymetry was gridded for a section of the California coast north of Santa Cruz to the Farallon Islands. Refraction coefficients were calculated for the portion of the ray path that traversed the northern bathymetry and for the portion of the ray path in Monterey Bay. The two refraction coefficients were multiplied together to determine a complete refraction coefficient.

Spectral refraction coefficients are provided in Excel spread sheets for each of 20 stations around Monterey Bay (Figure 2). The latitude and longitude of the station locations are provided in an Excel spread sheet.

References:

Dobson, R.S., 1967, Some applications of a digital computer to hydraulic engineering problems. Dept. of Civil Engineering, Stanford University Tech Report No. 80.

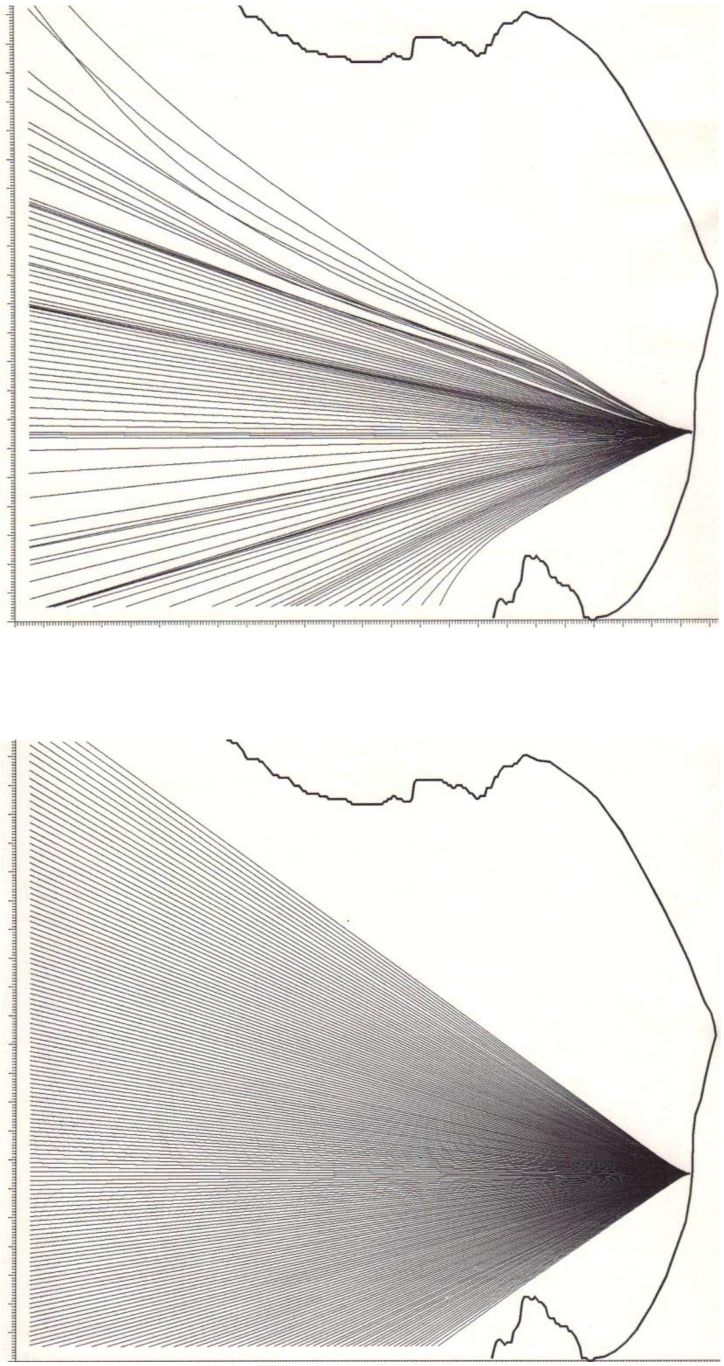

Figure 1.Upper Panel: Refraction diagram for 0.06 Hz at Station 9. Lower Panel: Refraction diagram for 0.13 Hz at Station 9.

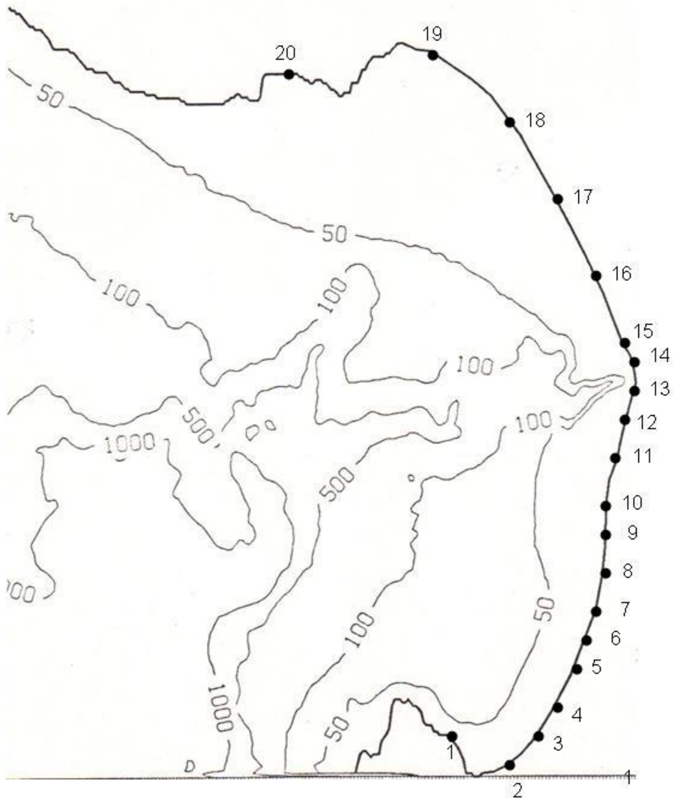

Figure 2. Bathymetry of Monterey Bay with approximate station locations.

Appendix 3

WAVE MODELING IN NORTHERN MONTEREY BAY

By Sea Engineering, Inc.

WAVE PROPAGATION MODELING OF MONTEREY BAY TO SUPPORT SEA LEVEL RISE IMPACTS

Prepared for:
ESA-PWA

November 30, 2012

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Introduction

Sea Engineering, Inc. (SEI) recently completed a wave modeling analysis for Monterey Bay (Bay) and near-shore Santa Cruz, CA. The objective of the task was to extract wave heights from the 10 meter depth contour at fifteen (15) distinct locations around northern Monterey Bay. The wave model, SWAN (Simulating WAves Near-shore), developed by Delft Hydraulics Laboratory, was utilized for all wave propagation modeling, and is described further below. A coarse-grid SWAN domain was initialized offshore to propagate waves from offshore Monterey Bay into the shorelines (Monterey Bay model). A near-shore, finer resolution, nested grid near Santa Cruz, CA, was incorporated to provide enhanced model accuracy, where applicable (Santa Cruz model). The model has been validated previously (Chang et al., 2010 – unpublished) and was adapted to fulfill the present task objectives.

Wave Model and Validation

As deepwater waves approach the coast, they are transformed by certain processes including refraction (as they pass over changing bottom contours), diffraction (as they propagate around objects such as headlands), shoaling (as the depth decreases), energy dissipation (due to bottom friction), and ultimately, by breaking. SWAN has the capability to model all of these processes in shallow coastal waters.

The SWAN model is a non-stationary (non-steady state) third generation wave model, based on the discrete spectral action balance equation, and is fully spectral (over the total range of wave frequencies). Wave propagation is based on linear wave theory, including the effect of wave generated currents. The processes of wind generation, dissipation, and nonlinear wave-wave interactions are represented explicitly with state-of-the-science, third-generation formulations.

The SWAN model can also be applied as a stationary (steady-state) model, which is how it was utilized for the present modeling effort. This is considered acceptable for most coastal applications because the travel time of the waves from the seaward boundary to the coast is relatively small compared to the time scale of variations in the incoming wave field, the wind, or the tide. SWAN provides many output quantities including two dimensional spectra, significant wave height, peak/mean wave periods, peak/mean wave directions and directional spreading. The SWAN model has been successfully validated and verified in laboratory and complex field cases globally.

NOAA National Data Buoy Center (NDBC) buoys within the domain (noted in Figure 1) were used for model validation during a previous field and modeling effort (Chang et al., 2010 – unpublished). Data from buoy 46236 were used to validate the model predictions for wave height, wave period and mean wave direction. Buoys 46092 and 46091 were used to validate wind speed and direction[1]. These buoys were selected based on the type of data that each recorded (i.e. Buoy 46236 did not record wind data, but recorded wave height and period). Buoy 46240 was located in shallow water near the southern Monterey Bay coastline, in an area not considered acceptable for deepwater model validation; therefore, its data were not used.

[1] Wind data were not used in the present modeling effort. However, wind data were used for model validation in the previous data collection and modeling effort, and are described here for completeness.

The grid resolution of the Monterey Bay domain was approximately 0.001° degrees in latitude and longitude (approximately 100 m grid spacing in x and y). The Monterey Bay model domain is shown in Figure 1.

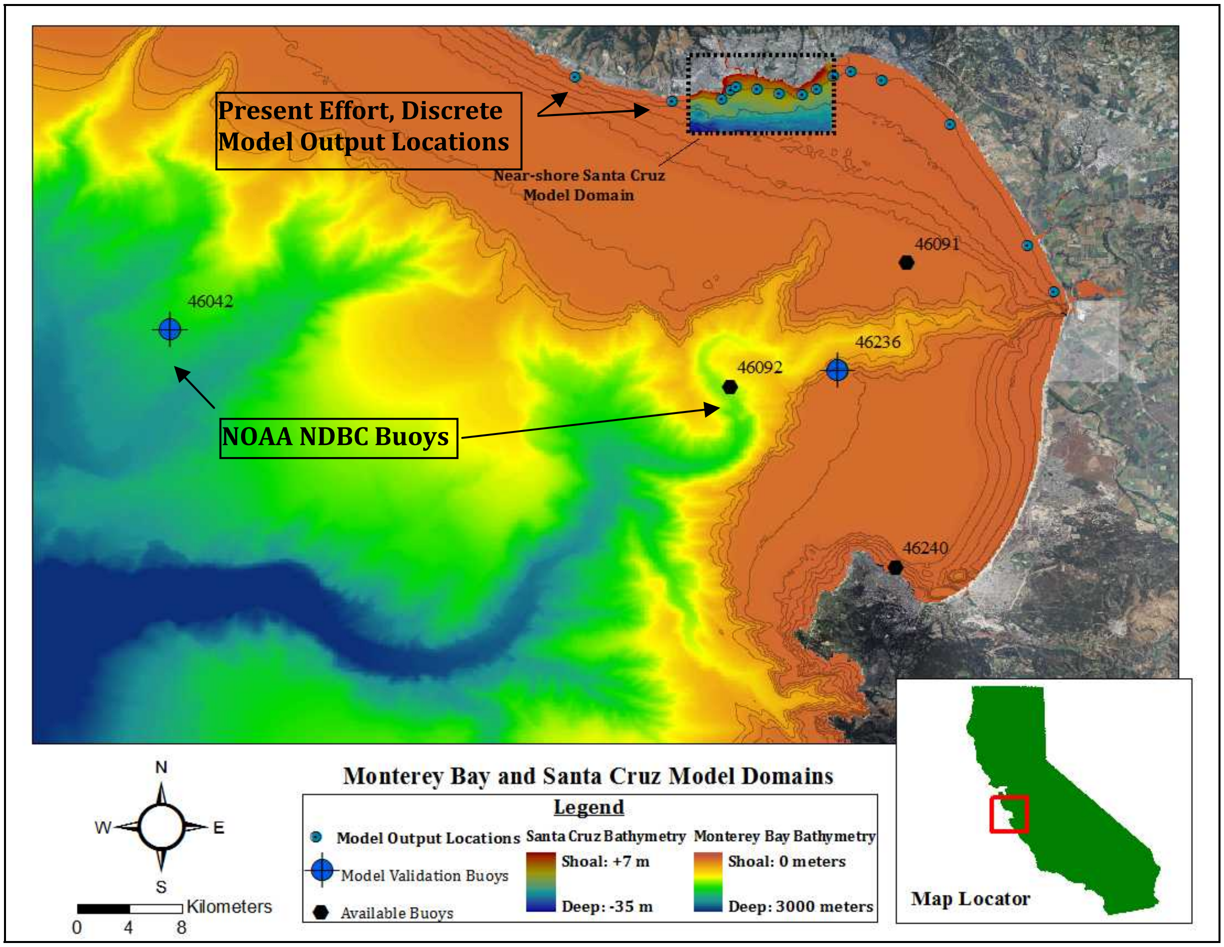

Figure 1. Monterey Bay and nested Santa Cruz model domains.
Also shown are NOAA NDBC buoy locations and model output locations.

The location of the finer-resolution, Santa Cruz model domain relative to the Monterey Bay domain is also shown in Figure 1. The grid resolution of the Santa Cruz model grid was approximately 0.0001° degrees in latitude and longitude (approximately 10 m in x and y). Wave spectra data were extracted from the Monterey Bay model grid results and were applied as boundary conditions along the offshore boundaries of the Santa Cruz model grid.

An expanded view of the Santa Cruz model domain is shown in Figure 2. A Datawell Directional Waverider wave buoy (DWR-G) was deployed in the near-shore to validate the Santa Cruz model. The buoy measured wave heights, periods and wave directions during the period of study. It was deployed approximately 100 m south of the Santa Cruz Bight shoreline.

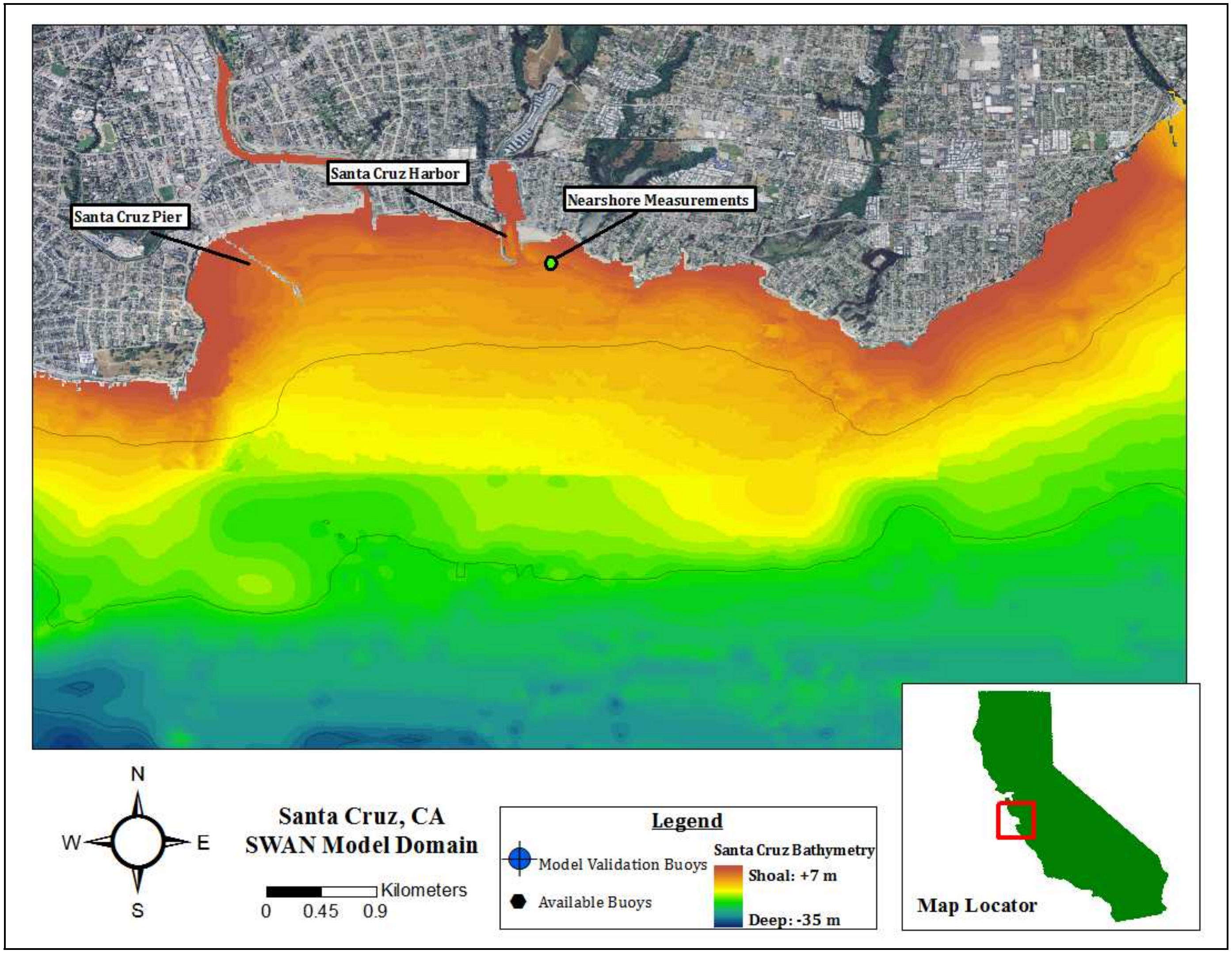

Figure 2. Santa Cruz model domain. Near-shore wave buoy measurement location is shown for reference.

Wave Model Validation

Wave heights (in meters), peak wave periods (in seconds) and mean wave direction (in degrees relative to True North) were exported from the Monterey Bay model for validation with local NOAA National Data Buoy Center (NDBC) buoys in Monterey Bay. Data were exported from the model every hour at several discrete buoy locations for direct comparison. NOAA NDBC buoy #46236 was selected as best representative for comparison due to its central Monterey Bay location. Modeled vs. measured data results during the period of study are shown in Figure 3.

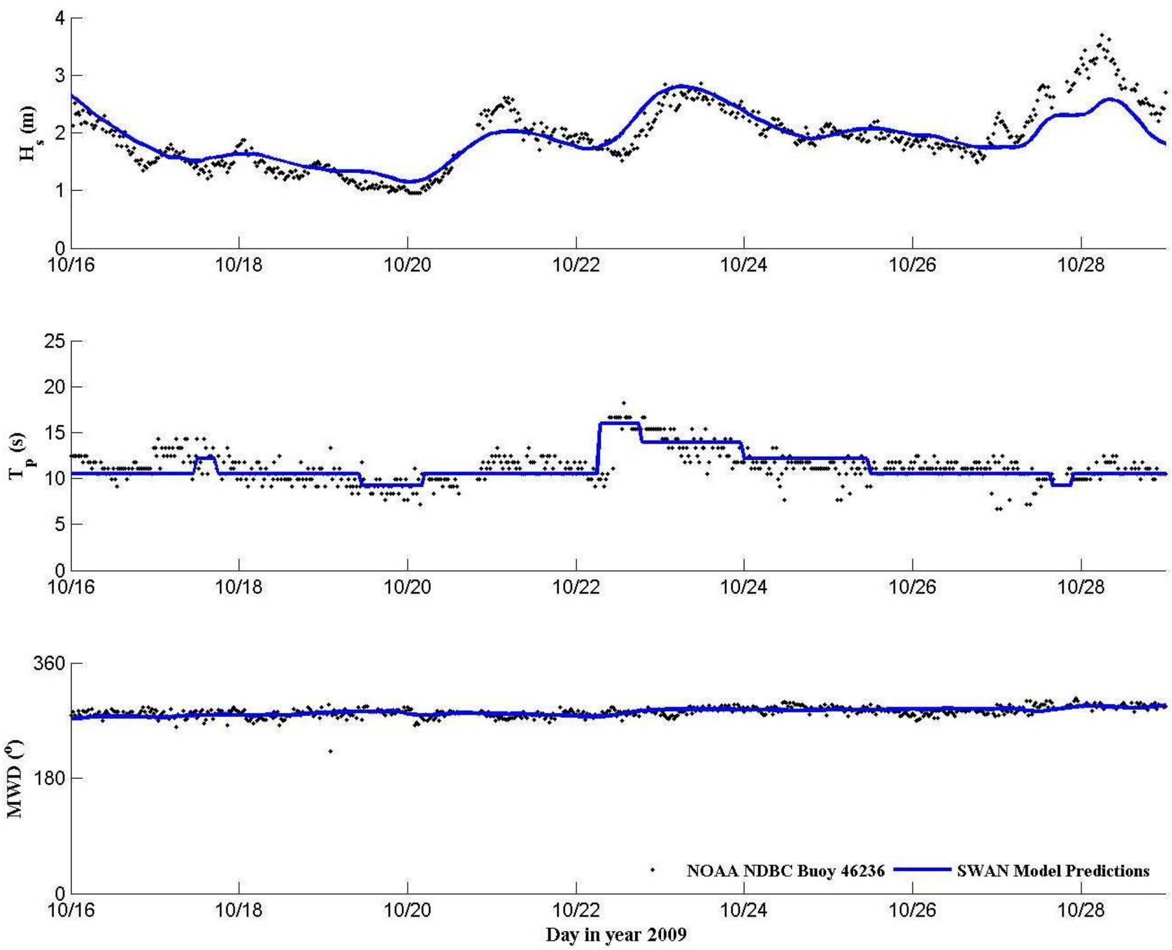

Figure 3. Model (line) representing the wave height (Hs), peak wave period (Tp) and mean wave direction (MWD) obtained from the Monterey Bay SWAN model. Measured data (dots) were obtained from the NOAA NDBC buoy 46236 in Monterey Bay.

The ability of a wind-wave model to predict wave characteristics can be evaluated in many ways. Here, model performance analysis (model vs. measured) was assessed through the computation of a scatter index (SI), the root mean squared error (RMSe) and the bias, or mean error (ME). A scatter index (Komen et al. 1994) is defined as the root mean squared error normalized by the average observed (measured) value. Bias, or mean error allows for the detection and evaluation and of bias in the wave characteristic data forecasts. When examining results of ME analysis, a positive value would indicate the average over-prediction of an observed value while a negative value indicates average under-prediction of the observed value.

The model performance statistics computed from the Monterey Bay model showed good agreement between modeled and measured values (Table 1). The wave heights showed a mean error of -0.06 m, approximately (i.e. model under-predicted the measured data on average). The peak periods also showed a slight under-prediction (-0.4 seconds, approximately). The mean wave directions were over-predicted by approximately 6 degrees (clockwise) from the measured data. All values are considered within good agreement.

Table 1. Model error statistics for the Monterey Bay SWAN model.

Data	RMSe	SI	ME
Hs	0.293	0.174	-0.059
Tp	2.781	0.255	-0.369
Dir	21.587	0.077	6.336

Wave heights, peak wave periods and mean wave directions were also exported each hour from the Santa Cruz model for comparison to measured Datawell Waverider data. Figure 4 shows a comparison of the model results to the buoy measurements. The model performance statistics computed from these data also showed good agreement of model to data (see Table 2). The wave heights showed a mean error of 0.04 m, approximately. The peak periods also showed a slight over-prediction of approximately 0.4 seconds. The mean wave directions were under-predicted by approximately 1.5 degrees (counter-clockwise) from the measured data. All model performance values presented here are considered in good agreement.

Table 2. Model error statistics for the Santa Cruz SWAN model.

Data	RMSe	SI	ME
Hs	0.185	0.218	0.038
Tp	1.197	0.091	0.365
Dir	6.916	0.033	-1.53

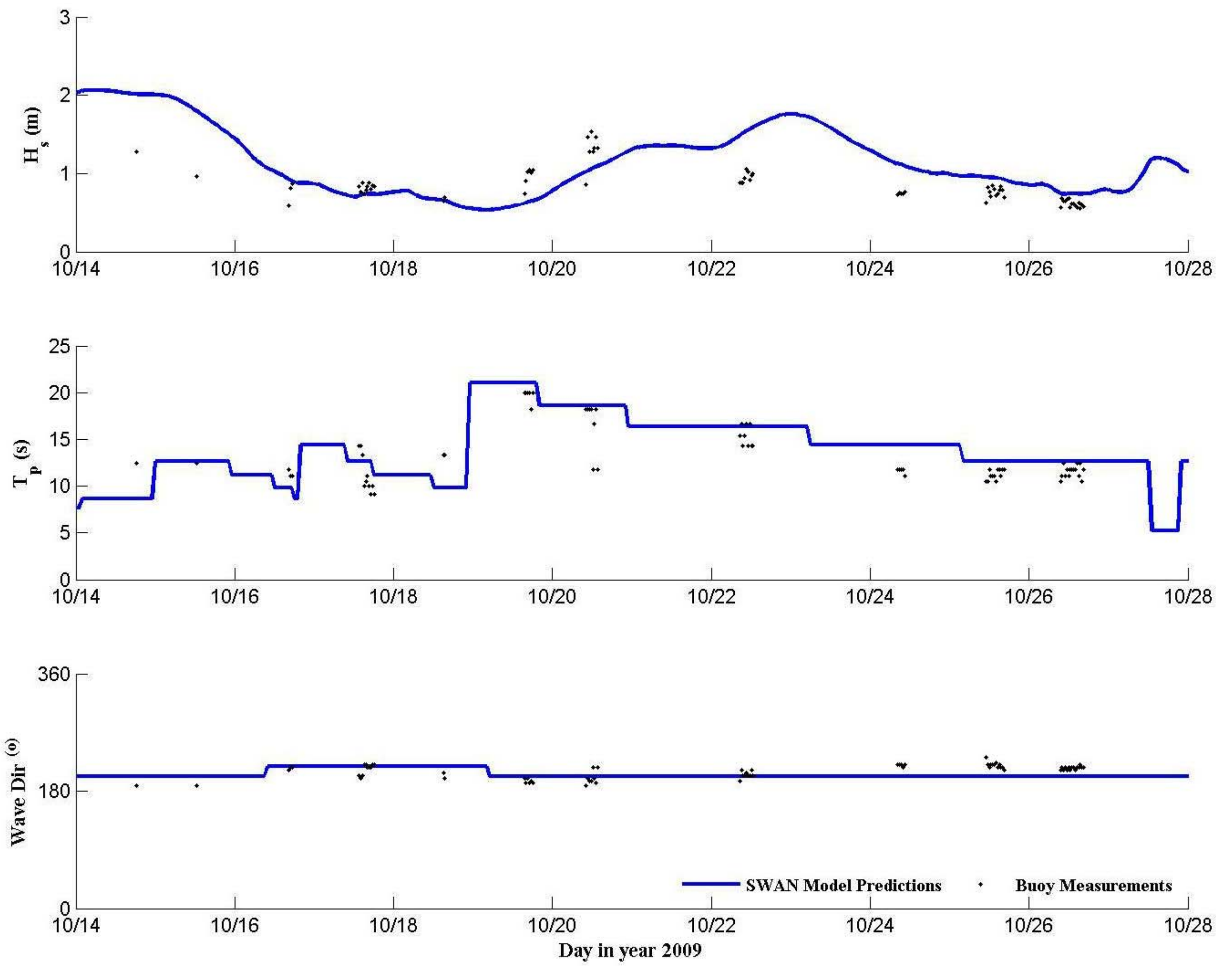

Figure 4. Model (line) representing the wave height (Hs), peak wave period (Tp) and mean wave direction (MWD) obtained from the Near-shore Santa Cruz SWAN model. Measured data (dots) were obtained from the Datawell DWR-G buoy deployed during the field study.

Present Wave Modeling Effort

The present modeling task objective was to export modeled wave conditions at fifteen (15) near-shore locations based upon a variety of specified boundary conditions. Wave height, wave period and wave direction were applied at the offshore boundaries of the Monterey Bay model domain (values are shown in Table 3).

A total of 121 wave cases were modeled: Significant wave heights were held constant at 1.0 m at the offshore boundaries; and each peak wave direction was coupled with each peak wave period (11 x 11 cases). JONSWAP wave spectra were generated from the applied offshore boundary conditions and propagated shoreward.

The fifteen model output locations were selected along northern Monterey Bay, a portion of which fell within the boundaries of the nested Santa Cruz model domain. Where possible, model outputs were extracted from the nested model results (locations 3 through 9).

The coordinates for each location are listed in Table 4. For reference, all model output locations are plotted on the Monterey Bay model domain in Figure 5 and Figure 6 (expanded view). The model output locations from solely the Santa Cruz model domain are shown in Figure 7.

Table 3. Modeled offshore wave boundary conditions.

Significant Wave Height (m)	Peak Wave Period, Tp (sec)	Peak Wave Direction (deg from True North)
1	4	185
1	6	200
1	8	215
1	10	230
1	12	245
1	14	260
1	16	275
1	18	290
1	20	305
1	22	320
1	25	335

Table 4. Model output locations and descriptions.

Location	Longitude	Latitude	Description
1	-122.125696	36.961744	4 Mile
2	-122.059121	36.945726	Natural Bridges
3	-122.025653	36.946822	The Lane
4	-122.0197	36.952942	Cowells
5	-122.015896	36.955138	Main Beach
6	-122.001397	36.953758	The Harbor
7	-121.986098	36.950859	26th Ave.
8	-121.970431	36.949909	Pleasure Point
9	-121.960365	36.95356	The Hook
10	-121.949341	36.962564	Capitola
11	-121.937347	36.965718	New Brighton
12	-121.915523	36.960033	Aptos
13	-121.868679	36.929859	Manresa
14	-121.816132	36.846133	Pajaro River
15	-121.797722	36.814919	Moss Landing Dunes

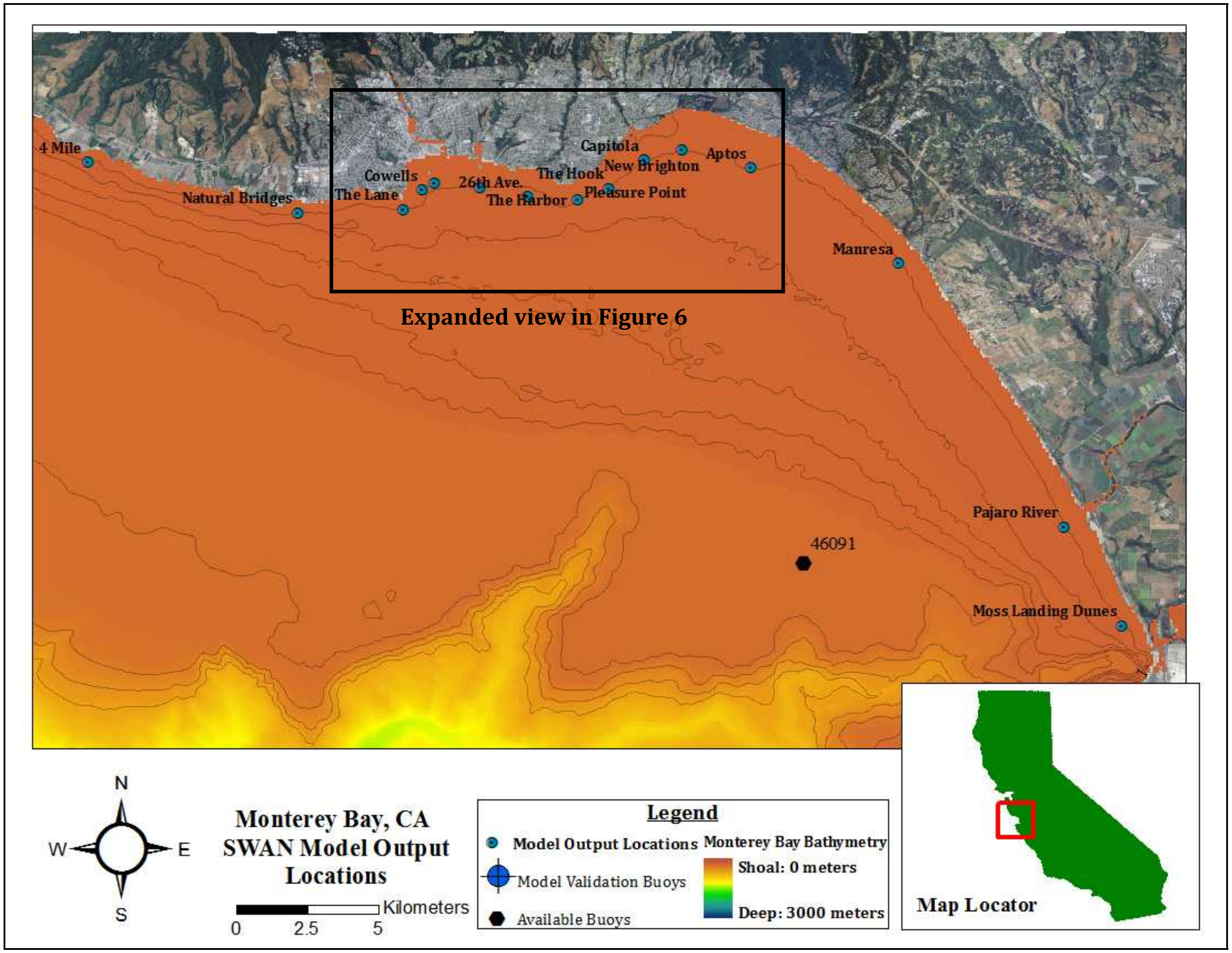

Figure 5. Expanded view of Northern Monterey Bay domain and model output locations at the 10-meter depth contour. Data at locations 1-2 and 10-15 were extracted from the Monterey Bay model results. Data at locations 3-9 were extracted from the Santa Cruz model results.

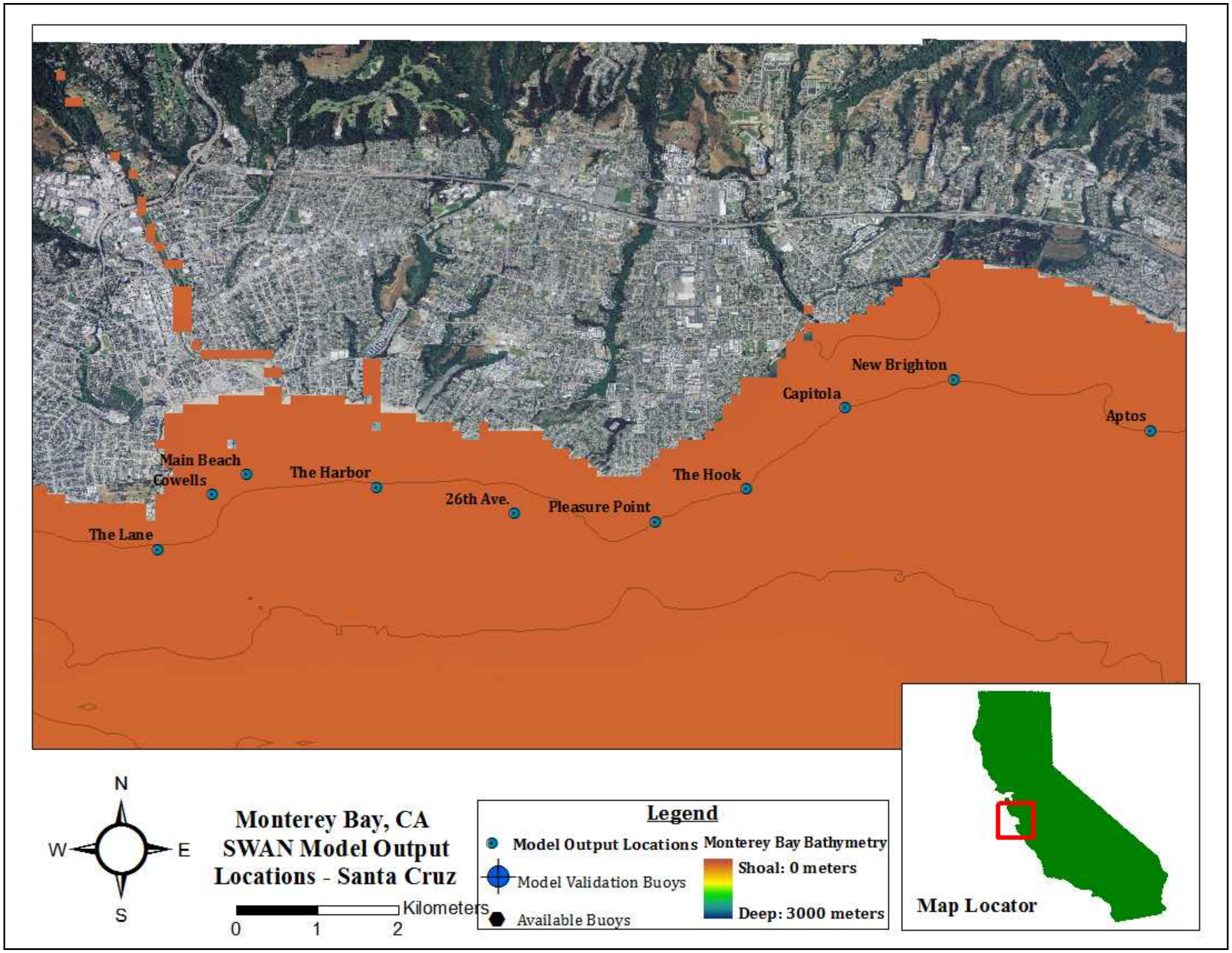

Figure 6. Expanded view of Figure 6 (for reference) showing detail of near-shore Santa Cruz model output locations.

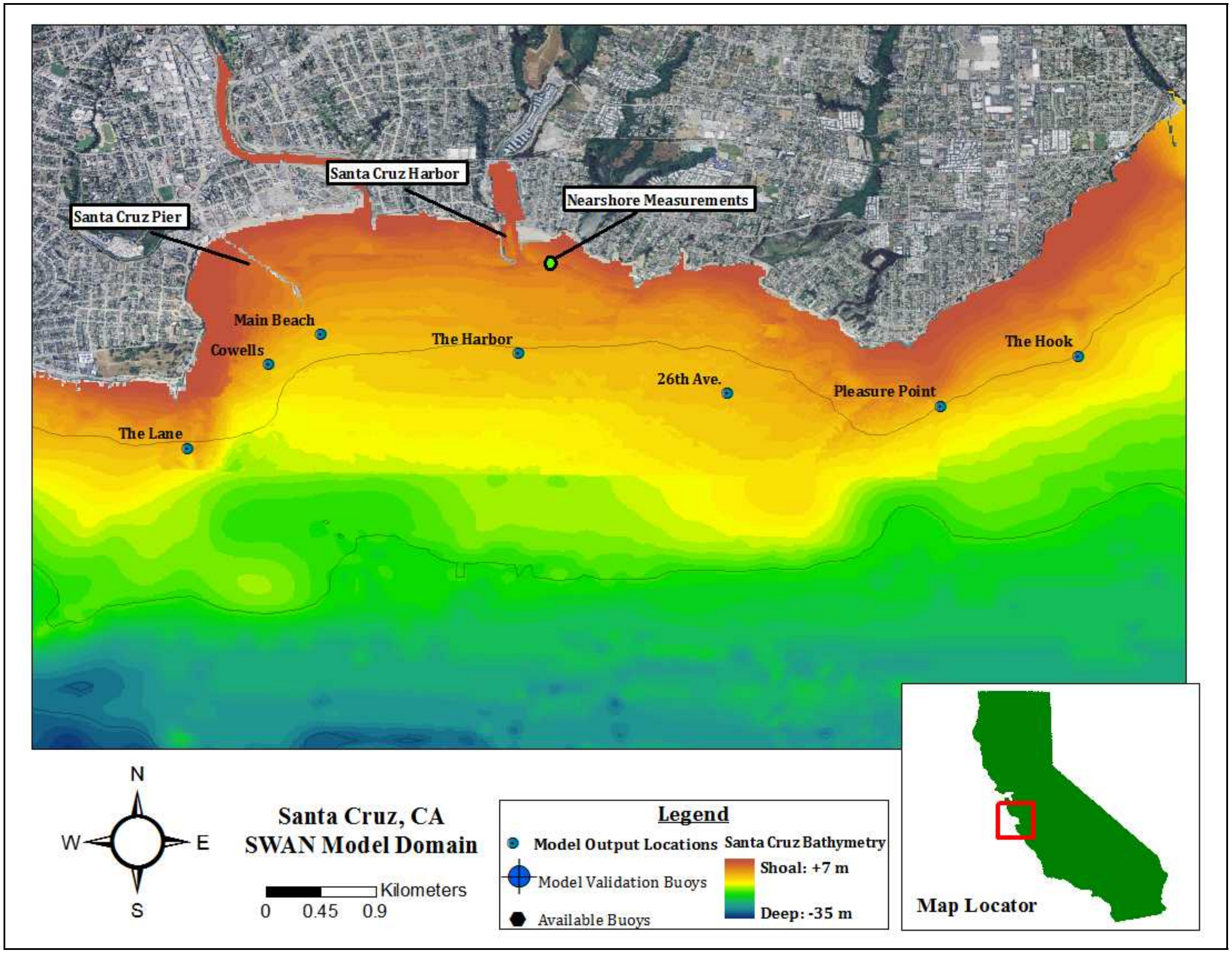

Figure 7. Santa Cruz model domain showing near-shore model output locations 3-9.

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Chang, G and C. Jones, D. Hansen, M. Twardowski and A. Barnard. 2010. Prediction of Optical Variability in Dynamic Near-shore Environments: Task Completion Report #3 – Numerical Modeling and Verification. 28 pp (unpublished).

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselman, S. Hasselman, and P.A.E.M. Janssen (1994) Dynamics and Modeling of Ocean Waves, Cambridge University Press, New York, 532 pp.

Appendix 4

SWAN MODEL CALIBRATION FOR NORTHERN SANTA CRUZ COUNTY

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memorandum

date 3/29/13

to Dave Revell, Bob Battalio

from To Dang

subject SWAN Model Calibration and Comparison between SEI and ESA PWA

project D211906.00 – Monterey Bay Sea Level Rise Vulnerability Assessment

1. Introduction

This memorandum describes how an existing ESA PWA in-house Simulating WAves Nearshore (SWAN) model was calibrated to match the SWAN outputs from a model developed by Sea Engineering, Inc. (SEI). The ESA PWA SWAN model was calibrated by changing the physical processes and model parameters to match the SWAN-model output from SEI at Four Mile (Figure A4-1). The different model setups between ESA and SEI for SWAN model are given in Table A4-1.

2. Calibration Procedure

The following procedure was used to calibrate the existing ESA PWA SWAN model for Northern Santa Cruz County using SWAN model outputs from SEI:

- Select a typical swell wave from SEI which has the wave input of Hs = 1 m, Tp = 20 s and Dp = 275^{o} and the wave output of Hs = 0.98 m at the depth of d = 10 m.

- Turn on and off physical processes such as GEN3, Triad etc.

- Change the model parameters such as water level correction factor, peak enhanced factor, friction coefficient, directional spreading empirical parameters etc.

- Previous ESA PWA-refraction-coefficient (Kr) and SEA-nearshore-transformed-coefficient (i.e. SWAN model output without removing shoaling coefficient Ks), SEI shoaling coefficient at d = 10 m, SEA-refraction coefficient (after dividing swan model output by shoaling coefficient) and difference between two refraction coefficients are given as

Hs (m)	Tp (s)	Dp (o)	Kr_ESAPWA	KrKs_SEI*	Ks_SEI	Kr_SEI	DIFF
1	20	275	**0.56**	**0.98**	1.287	0.76	0.2

The SEA-nearshore-transformed-coefficient (KrKs_SEI= 0.98) is the near shore wave height (Hs = 0.98 m) from the SWAN output. This value was calibrated with near-shore buoy data.

3. Results

- To match the depth (d = 10 m) from SEI model output for Four Mile, the current water level correction is set as WL = -9.649.

- The bottom friction coefficient of the JONSWAP formulation is equal to 0.067 m^2s^{-3} for wind sea conditions (default value) and equal to 0.038 m^2s^{-3} for swell conditions. The current bottom friction coefficient is set as 0.038 m^2s^{-3}.

- The depth-induced breaking in shallow water is Battjes and Janssen (1978) model. The coefficient (α) for determining the rate of dissipation (default = 1.0) and gamma (γ) the value of the breaker parameter defined as $\gamma = H_m/d$ (default = 0.73). The current values of these coefficients are $\alpha = 1$ and $\gamma = 0.8$.

- The peak enhanced factor for JONSWAP spectrum is $\gamma = 3\sim10$ (default = 3.3). For swell $\gamma = 8\sim10$, the current value of peak enhanced factor is $\gamma = 10$.

- The current one-sided directional width of the spectrum is set to 7.3° corresponding to ms = 60 (for narrow spectrum width).

- The non-linear triad interactions (LTA) have the default values of $\alpha = 0.10$ and $\beta = 2.2$. The calibration process were done by changing $\alpha = 0.10^{-5}$ and $\beta = 2^{-10}$ in triad module to match SEI model output (H_s = 0.98 m). After many runs, selected SWAN wave output from ESA PWA are given below.

TRIAD		X_p	Y_p	Depth	H_{sig}	Dir	RT_{peak}
α	β	[m]	[m]	[m]	[m]	[degrees]	[sec]
2	2	577832	4090986	10	0.7502	231.02	20
2	3	577832	4090986	10	0.8294	229.57	20
2	4	577832	4090986	10	0.7809	230.77	20
2	5	577832	4090986	10	0.7808	230.77	20
3	**3**	**577832**	**4090986**	**10**	**0.9732**	**228.70**	**20**
3	3.2	577832	4090986	10	0.9714	228.72	20
3	4	577832	4090986	10	0.8668	229.72	20

- The closely matched SEI-wave-height (H_s = 0.98 m) is the case where the tuning coefficients have $\alpha = 3$ and $\beta = 3$. This gives Hs = 0.97 m and d = 10m. The wave pattern for this case can be seen in Figure A4-2.

- It is notes that the wave refraction coefficient *Kr* for ESAPWAS is 0.756 smaller than 0.97 Since $H_i = K_r \cdot K_s \cdot H_o \Rightarrow K_r = H_i / (K_s \cdot H_o)$ = 0.97 m / (1.287×1m)=0.756.

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Table A4-1: SWAN model setup between SEI and ESA PWA

SEAI		ESA PWA		SAME/DIFFERENT
Boundary Conditions		Boundary Conditions		
BOUND SHAPESPEC	JONSWAP 3.30 PEAK DSPR POWER	BOUND SHAPESPEC	JONSWAP 3.30 PEAK DSPR POWER	SAME
BOUNDSPEC SIDE N CON PAR	1 4 305 10	BOUNDSPEC SIDE N CON PAR	1 4 305 10	
BOUNDSPEC SIDE W CON PAR	1 4 305 10	BOUNDSPEC SIDE W CON PAR	1 4 305 10	
BOUNDSPEC SIDE S CON PAR	1 4 305 10	BOUNDSPEC SIDE S CON PAR	1 4 305 10	
Physical Processes		Physical Processes		
GEN1		GEN3		Different: 1st vs 3rd SWAN generation mode
BREAKING		BREAK CON	1.00 0.73	What is the value of fric. coef?
FRICTION JONSWAP		FRIC JON	0.0670	What is the value of fric. coef?
TRIAD		OFF TRIAD		Different: ESA turned off TRIAD
OFF QUADRUPL		OFF QUAD		Same: both turned off QUADRUPL
PROP BSBT		PROP S&L		Different: BSBT vs S&L numerical scheme

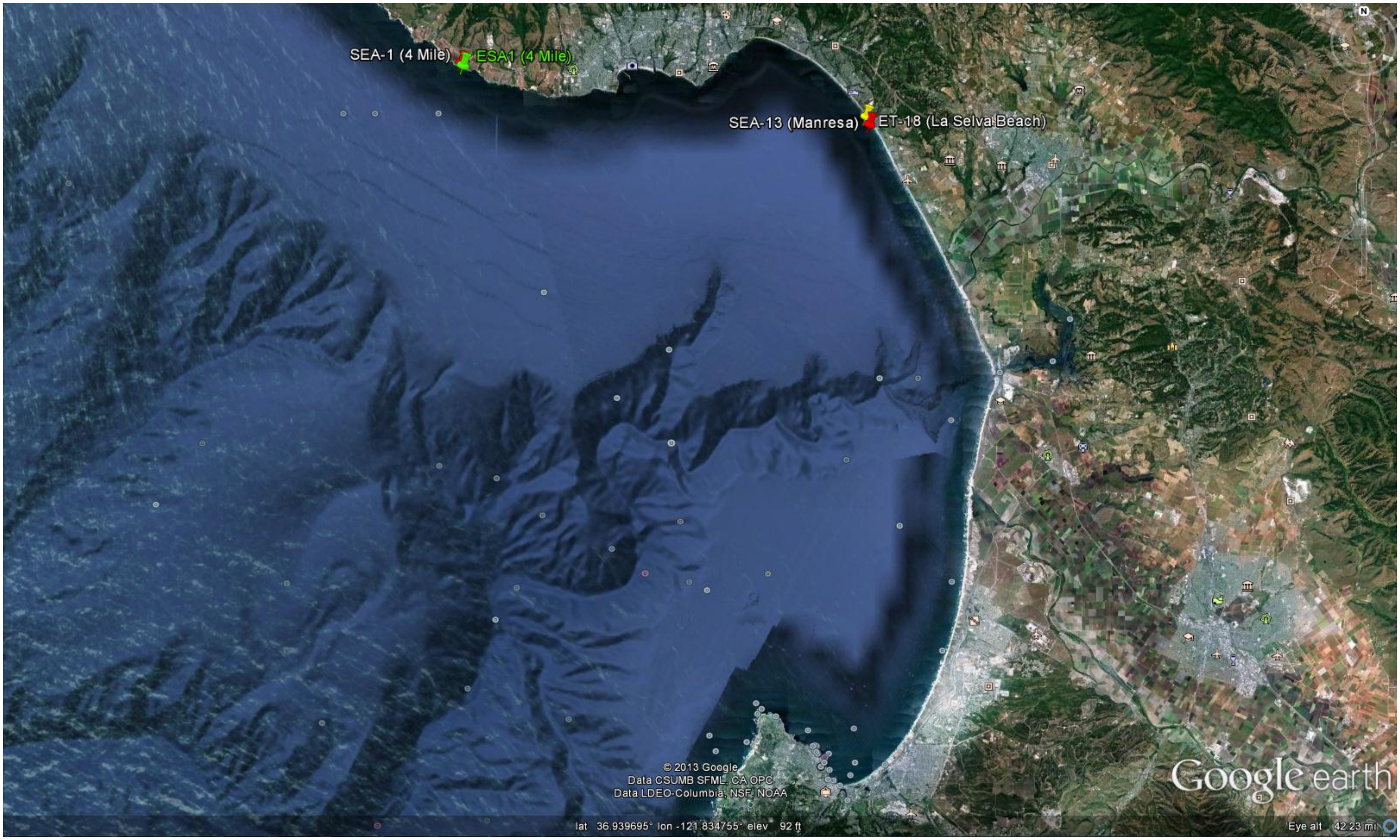

Figure A4-1: Location of Four Mile Transformation Point

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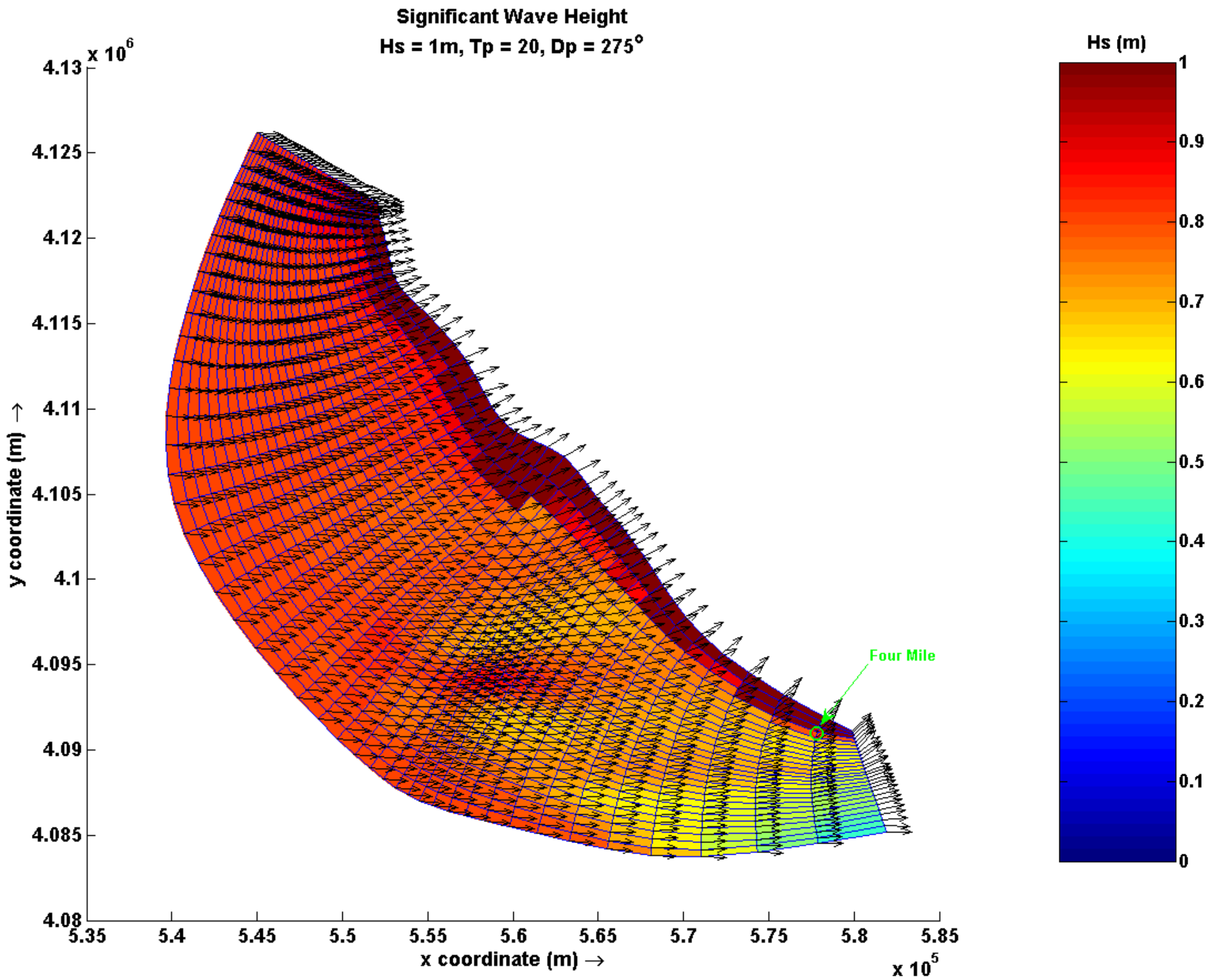

Figure A4-2: SWAN Model Wave Pattern for Hs = 1 m, Tp = 20 s and Dp = 275 for Four Mile

Appendix 5

APPROACH TO OVERTOPPING CALCULATIONS

Appendix 5. Approach to Overtopping Calculations, by Reach

<table>
<tr><th>Region</th><th>Crest Elevation</th><th>Flooding Limit</th><th>Hypsometry</th></tr>
<tr><td>Santa Cruz, North of River</td><td colspan="3">Overtopping not used in this region. A high levee along the San Lorenzo River protects this region from wave overtopping. This area was highlighted as “low-lying,” with the area delineated using the 100-year tide + 1 foot for wave set-up.</td></tr>
<tr><td>Santa Cruz, Boardwalk</td><td>Crest elevation is the maximum of (1) future crest, as estimated using inward erosion of crest on existing topography and (2) existing toe elevation raised by sea level rise. By 2100 the lifted toe elevation dominates.</td><td>None</td><td>No modification (no connectivity with ocean)</td></tr>
<tr><td>Santa Cruz, Neary Lagoon</td><td rowspan="2">Crest elevation is the maximum of (1) future crest, as estimated using inward erosion of crest on existing topography and (2) existing toe elevation raised by sea level rise. Crest elevations dominate, except for s32100.</td><td>None</td><td>Fill above existing water surface elevation, raised by sea level rise.</td></tr>
<tr><td>Santa Cruz, Downtown</td><td>None</td><td>No modification (no connectivity with ocean)</td></tr>
<tr><td>Capitola</td><td>Crest elevation is the maximum of (1) future crest, as estimated using inward erosion of crest on existing topography and (2) existing toe elevation raised by sea level rise. Lifted toe elevation dominates for sea level rise amounts greater than ~30 cm.</td><td>None</td><td>Well-connected region - fill above 100-yr tide, raised by sea level rise.</td></tr>
<tr><td>Aptos</td><td>Future crest elevations predicted by erosion hazard zones do not correspond to exceeded elevation necessary to overtop into the low-lying areas of Aptos. A high parking lot behind the beach has an elevation of approximately 4 m NAVD. All crests are set to this elevation until the parking lot has been eroded, at which point the Capitola rules (see above) are applied.</td><td>None</td><td>Well-connected region - Fill above 100-yr tide, raised by sea level rise.</td></tr>
<tr><td>Roberts Lake & Laguna Grande</td><td>First dune crest not representative of overtopping elevation – used top of dune instead. No dunes show complete erosion by 2100, so crest elevation remains constant and no overtopping occurs. Exception is the Canyon Del Rey Blvd underpass, which was modeled individually. Future crests are higher than toe elevation raised by SLR.</td><td>If the predicted WSE is > than the crest elevation, set flood elevation to crest (can't fill higher than that). This is only triggered for s32100.</td><td>Fill above 3.4 m or the 100-yr tide level (whichever is higher). 3.4 m corresponds to the existing lake surface elevation rounded up to the nearest 0.1 meters.</td></tr>
<tr><td>El Estero & Del Monte Lake</td><td>First dune crest not representative of overtopping elevation – used top of dune instead. This elevation remains constant unless dune is eroded through, in which case the crest elevation decreases with existing topography. Crest elevation is the maximum of (1) future crest, as estimated using inward erosion of crest on existing topography and (2) existing toe elevation raised by sea level rise.</td><td>Minimum of the predicted water surface elevation or the maximum of the existing toe raised by sea level rise or the minimum existing crest (unmodified). The minimum crest dominates.</td><td>Fill above 1.9 m or the 100-yr tide level (whichever is higher). 1.9 m corresponds to the existing lake surface elevation rounded up to the nearest 0.1 meters.</td></tr>
</table>

Appendix 6

METHOD FOR ESTIMATING OVERTOPPING VOLUMES

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memorandum

date February 21st, 2014

to Elena Vandebroek

from To Dang

project Monterey Bay Sea Level Rise Vulnerability Study (D211906.00)

subject Overtopping Volume Calculations

This memo describes the methodology for calculating the overtopping rates and total volume during a major coastal flood event. Wave overtopping occurs when the barrier crest height is lower than the potential runup elevation. If the potential total runup elevation exceeds the crest elevation, *Rc*, then the structure or barrier is overtopped and should be evaluated to define the coastal storm flood hazard zones.

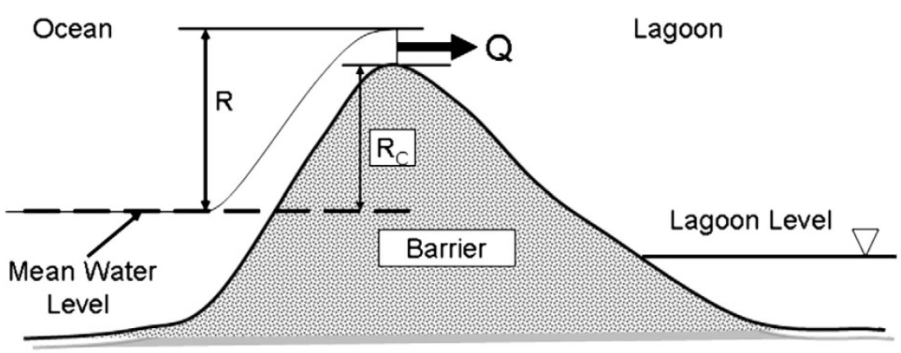

Figure Source: Laudier et al., 2011

Wave overtopping may be predicted by a number of different methods. Most commonly, practitioners use semi-empirical equations that have been fitted to hydraulic model tests using irregular waves for specific structure geometries. One of the empirical equations, by Pullen et al. 2007, is popularly adopted:

$$\frac{q}{\sqrt{gH^3}} = \frac{A}{\sqrt{m}} \cdot I_b \cdot \exp\left[-B\frac{R_c}{(\gamma_r I_b H)}\right], \qquad I_b \le 2 \text{ (breaking wave)} \qquad (1)$$

$$\frac{q}{\sqrt{gH^3}} = C \cdot I_b \cdot \exp\left[-D\frac{R_c}{(\gamma_r H)} I_b\right], \qquad I_b \ge 2 \text{ (non-breaking wave)} \qquad (2)$$

Where: q = average discharge per unit length of structure ($m^3/s/m$)

H = significant wave height at the toe of the structure (m),
g = gravitational acceleration (m/s^2)
R_c = barrier crest elevation relative to the still water level datum (m)
I_b = Iribarren number (unitless)
m = beach slope (unitless)
γ_r = reduction coefficient (unitless)

The coefficients are empirically specified using laboratory data:
A = 0.067
B = 4.75
C = 0.2
D = 2.6

To predict the wave overtopping volumes in terms of the total water level and crest elevation, the previous equations can be re-written as follows:

$$\frac{q}{\sqrt{gH}} = \frac{A}{\sqrt{m}}\left(\gamma_r \frac{R_2}{1.5}\right)\cdot \exp\left[-B\frac{R_c}{\left(\gamma_r \frac{R_2}{1.5}\right)}\right], \quad I_b \le 2 \text{ (breaking wave)} \tag{3}$$

$$\frac{q}{\sqrt{gH}} = C\left(\gamma_r \frac{R_2}{1.5}\right)\cdot \exp\left[-D\frac{R_c}{\left(\gamma_r \frac{R_2}{1.5}\right)} I_b\right], \quad I_b \ge 2 \text{ (non-breaking wave)} \tag{4}$$

Where: $R_2 = 1.5 \cdot I_b \cdot H$ is the wave runup height or the total water level with respect to the still water level datum.

For natural beaches such as the Carmel River in California, Laudier et al. (2011) tuned the overtopping model (Eq. (1) and Eq. (2)) to fit the field data using a reduction factor, γ_r, to account for beach permeability, berm characteristics, non-normal wave incidence, and surface roughness ranging from 0.6 – 0.8.

The runup height (or the total water level) was calculated using the composite slope method. The crest height (or the crest elevation) was identified along the beach profile, and a reduction factor of γ_r=0.6 was adopted. A 4–hour storm with a triangular hydrograph was assumed to reflect a major wave event coinciding with a high tide. The outcome of this analysis was a set of look-up tables (one for each of the flood analysis profiles) reporting overtopping volume per length of shoreline (m^3/m) versus negative freeboard (the crest elevations minus the total water level (i.e., $F = R_c - R_2$)). These tables were then used to calculate overtopping volumes for a series of closely spaced profiles to capture the along-shore variability inherent in the Monterey Bay study area.

References

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Pullen, T., Allsop, N.W.H., Bruce, T., Kortenhaus, A., Schuttrumpf, H., van der Meer, J.W., 2007. EurOtop: Wave Overtopping of Sea Defenses and Related Structures: Assessment Manual. Available at: www.overtopping-manual.com.