FINAL

SANTA BARBARA COUNTY COASTAL HAZARD MODELING AND VULNERABILITY ASSESSMENT

Technical Methods Report

Prepared for
County of Santa Barbara

August 3, 2015

Tarantulas, looking towards Jalama Beach County Park. Photo by J. Jackson, May 2015.

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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 south coast of Santa Barbara County, California, extending from Jalama Beach County Park to Rincon Point (Figure 1). This report supplements the metadata associated with each geospatial dataset by documenting the input data, methods and assumptions used to generate these hazard zones.

1.2 Background

The Santa Barbara County Coastal Hazard Modeling and Vulnerability Assessment Project is modeled after The Nature Conservancy's Building Coastal Resilience for Disaster Risk Reduction and Climate Adaptation project.[1] Specifically, the County of Santa Barbara's (County) project approach tiers off of the Coastal Resilience Ventura project.[2] ESA, the County of Santa Barbara and others are working with local communities to assess the County coastline's vulnerability to potential future impacts of sea level rise. Santa Barbara County is a valuable economic and environmental section of the California coast. Much of the County coast is eroding, including almost all cliffs and approximately one third of the beaches. Some of the developed areas are in the 100-year flood plain under existing conditions. Both erosion and flooding are expected to increase with sea level rise. There is also a risk of increased rainfall intensity that will increase 100-year storm flood extents along creeks. The County contracted ESA to assess the potential impacts of sea level rise on coastal hazards of erosion, flooding and inundation.

As part of this project, the County and ESA facilitated a stakeholders group. The stakeholders include planning and public works representatives from the Cities of Goleta, Carpinteria and Santa Barbara as well as the County and The Nature Conservancy. The project was funded by the State of California Coastal Conservancy's Climate Ready Grant Program. This funding is available to encourage local governments to to develop and adopt updated plans that conserve and protect coastal resources from future impacts from sea-level rise and related climate change impacts such as extreme weather events.

[1] http://coastalresilience.org/

[2] A partnership project with Ventura County, Naval Base Ventura County, and the incorporated Cities of Ventura, Oxnard and Port Hueneme and the Nature Conservancy.

1.3 Previous Coastal Hazards Analysis

Multiple coastal hazards assessments already exist for the Santa Barbara 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 and are believed to underestimate coastal flood hazards. FEMA is currently updating coastal flood hazard maps according to the 2005 Pacific Coast Guidelines (FEMA 2005a). 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. Provisional maps are expected in 2016 (personal communication with FEMA IX).

- 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://coast.noaa.gov/slr/) 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. 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. (PWA, now ESA) 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, PWA projected future coastal flooding hazards for the entire state based on a review of existing FEMA hazard maps. In addition, 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. The 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. These "Pacific Institute" maps based on PWA (2009) were used in an environmental impact report by AMEC (2010) on the General Plan for the City of Santa Barbara. The Pacific Institute – PWA maps did not extend beyond the Santa Barbara Harbor but the AMEC report developed maps of inundation due to sea level rise using elevation only (also known as "bath tub" contour mapping because hydraulic connectivity is presumed, with no consideration of erosion or hydrodynamics). See Figure 2 and Figure 2 for examples (source Griggs and Russel, 2012).

- Since in 2011, ESA and the Goleta Slough Management Committee have worked together to develop a management plan that addresses sea level rise in the Goleta Slough area. The Goleta Slough Area Sea Level Rise and Management Plan is still in draft form but is expected to be finalized and published in August 2015 (ESA & GSMC, 2015).

- Griggs and Russell (2012) completed a preliminary assessment of vulnerability of the City of Santa Barbara to sea level rise. This project used the exposure maps in the General Plan Update EIR (AMEC; 2010) described previously and shown in Figure 2 and Figure 3, as well as other scientific information and contemporary thought. The study recommended additional data collection and analysis, while providing an assessment highlighting the risks that wave damage, flooding and inundation, and erosion pose to shoreline development and infrastructure in Santa Barbara into the future, as well as the adaptive capacity for these hazards.

- The UCSB Bren School 2015 master's project, titled City of Santa Barbara Sea Level Rise Vulnerability Assessment[3], identified vulnerabilities within human populations, critical infrastructure, recreation and public access, and ecological resources, as well as identified adaptation strategies that the City can consider for their LCP update.

The present study has improved the methods from the Pacific Institute Study and applied them to the Santa Barbara County study area with higher resolution local data and review by local experts. This work builds upon enhancements developed during the mapping of Ventura County (ESA and Monterey Bay). The net result of these improved methods has been to produce projections of future coastal hazards that are suitable for local planning processes (e.g. LCP and General Plan updates, and permit applications).

1.4 Santa Barbara County Study Area

This study assessed coastal hazards along approximately 70 miles of coastline from Jalama Beach County Park to Rincon Point (Figure 3). Complicated tectonics form this coastline with varying levels of uplift and subsidence. The Channel Islands to the south shelter the coast from southerly waves creating a narrow swell window between Point Conception and the islands, and driving almost unidirectional sand transport from west to east toward Oxnard.

The coastline from Jalama south, around Point Conception and east to Gaviota State Park is characterized by a series of undeveloped eroding sea cliffs. The sea cliffs are intersected by a series of low-lying pocket beaches and small coastal lagoon systems. Cliff armoring and seawalls from Union Pacific Railroad reinforcements reflect the existing coastal hazards that are present along this stretch of coast. Similar sea cliff conditions exist eastwards, with sparse development and parks until Devereux Lagoon. Highly-developed sea cliffs with mixed armoring characterize the stretch of coast from Isla Vista to East Mesa in Santa Barbara, broken up by UCSB Lagoon, Goleta Slough, and a few smaller creek drainages. The Santa Barbara Harbor and low lying beachfront parks and other resources in downtown Santa Barbara are within the Mission Creek and

[3] The City of Santa Barbara Sea Level Rise Vulnerability Assessment can be found here: http://www.bren.ucsb.edu/research/2015Group_Projects/documents/SeaLevelRiseSB_Thesis.pdf

Sycamore Creek drainages. The coastline from the Andree Clark Bird Refuge to Toro Canyon is characterized by lower sea cliffs and dunes that are backed by development or the Union Pacific Railroad and intermittent coastal armoring. As the short cliffs drop to a lower dune backshore around Carpinteria Salt Marsh, the developed coastline is almost entirely armored by rock rip rap. East of Carpinteria Creek the coast is mostly cliffs with a few developed areas, the Union Pacific Railroad, and homes at Rincon Point, which marks the southern end of this study area. Additional information can be found in Griggs, Patsch and Savoy (2005).

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. A complete list of GIS deliverables is provided in Appendix 1. The data will be available from the county or viewed online at The Nature Conservancy's Coastal Resilience website (www.coastalresilience.org). Hazard zones were developed for existing conditions (2010) and three planning horizons (2030, 2060, and 2100) based on direction received during the County stakeholder process and consistent with the California Coastal Commission guidance on sea level rise (CCC, 2015). Three future sea level rise scenarios were assessed for each type of hazard. These scenarios are summarized in section 2.1 and are described in Section 4.1. All GIS deliverables are provided in the NAD 1983 datum and UTM Zone 11N projection. Horizontal units are in meters.

Dune Erosion Hazard Zones (Section 8.1 and 8.2, Figure 4):

These zones represent future long term and storm induced dune erosion hazard zones. Model results incorporate 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
  10 polygon shapefiles: Existing conditions eroded dune zone plus 3 planning horizons x 3 SLR scenarios

- Storm erosion hazard zones
  10 polygon shapefiles: storm erosion from existing dune plus 3 planning horizons x 3 SLR scenarios

- Spatially aggregated erosion hazard zones (long term and storm, see Section 11 for more detail)
  3 polygon shapefiles: one for each planning horizon and each erosion projection

Cliff Erosion Hazard Zones (Section 8.3 and 8.4, Figure 5):

These zones represent cliff erosion hazard zones projecting future cliff edge locations. These results are derived by incorporating site-specific historic trends in erosion, additional erosion caused by accelerating sea level rise, and a factor of safety to account for potential block failures (large sections of cliff that fail suddenly, a typical form of cliff erosion along the Santa Barbara County coast). 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
  10 polygon shapefiles: existing cliff zone plus 3 planning horizons x 3 SLR scenarios

- Cliff erosion with factor of safety hazard zones (potential large bluff failures)
  10 polygon shapefiles: existing cliff zone with potential block failure plus 3 planning horizons x 3 SLR scenarios

- Spatially aggregated erosion hazard zones (see Section 11 for more detail)
  3 polygon shapefiles: one for each planning horizon for each erosion projection

Coastal Storm Flood Hazard Zones (Section 9.1, Figure 6)

These hazard zones depict flooding caused by a coastal storm and are presented separately by mechanism. The processes considered include (1) elevated ocean levels due to climate effects (e.g. elevated water levels during El Nino phases) and storm surge (a rise in the ocean water level caused primarily by winds and pressure changes during a storm), (2) wave run-up (includes wave setup and waves running up over the beach and coastal property, calculated using the computed 100-year total water levels), (3) extreme lagoon water levels which can occur when lagoons fill up when the mouths are closed (using maximum potential beach berm elevations), and (4) additional flooding caused by rising sea level in the future. 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. For item (1) “elevated ocean levels”, the 100-year recurrence water level based on tide gauge data was used. Based on comments received, a lower and more frequent of extreme high monthly water level was also mapped (discussed in Extreme Monthly Inundation Zones, below).

- 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 appear to have a surface connection 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 11 for more detail)
  3 polygon shapefiles: one for each planning horizon for the above four mechanisms

Extreme Monthly Inundation Zones (Section 9.2, Figure 7 & Figure 8)

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, which is a high water level that is reached approximately once a month (1.99 m (6.53 ft) NAVD, calculated from SB Harbor Tide gauge data). 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 (Figure 7)
  10 polygon shapefiles: existing conditions and 3 planning horizons x 3 SLR scenarios

  Note: There are two types of inundation areas: (1) areas that appear to be 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" or "connectivity uncertain") in each geospatial dataset. We recommend these be mapped as separate colors, similar to the NOAA SLR Viewer (described in Section 0).

- Depth of water within the rising tide inundation zone (in meters) (Figure 8)
  10 rasters (1 meter cell size): existing conditions and 3 planning horizons x 3 SLR scenarios

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

- Spatially aggregated rising tide hazard zones (see Section 11 for more detail)
  3 polygon shapefiles: one for each planning horizon

Fluvial Flooding Hazard Zones (Section 10, Figure 9)

These zones show the area and depth (in meters) of flooding caused by the 100-year streamflow on Carpinteria Creek under existing and future conditions. 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.

- Area of flooded due to 100-year discharge on Carpinteria Creek
  10 polygon shapefiles: existing conditions and 3 planning horizons x 3 SLR scenarios

  Note: There exist flooded areas that are disconnected from the main channel flooding. These were left in because they are low laying adjacent areas that have the potential to flood and capture the uncertainty of the 1-dimensional model.

- Depth of water within flooded zones (in meters)
  10 rasters (1 meter cell size): existing conditions and 3 planning horizons x 3 SLR scenarios

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

- Spatially aggregated rising tide hazard zones (see Section 11 for more detail)
  3 polygon shapefiles: one for each planning horizon

Spatial Aggregation Relative Risk Zones (Section 11, Figure 10)

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 for a specific location. The higher the attributed number, the more likely the area is to become exposed to 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), sea level rise scenario, and planning horizon, as follows:

Dune and cliff erosion hazard zones:
Hazard zone type + _ + erosion projection type +_+ 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
coastal_floodhz –	Coastal storm flood hazard zone
coastal_floodhz_aggr –	Spatially aggregated coastal storm flood hazard zone
emhw_area –	Rising tide (Extreme Monthly High Water) inundation area
emhw_aggr –	Spatially aggregated rising tide zones
emhw_d –	Inundation zone depth in areas with a definite connection to ocean tides
fluvial –	Fluvial flooding hazard zone
fluvial_dep –	Fluvial flooding depths
fluvial_aggr –	Spatially aggregated fluvial flooding 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) for <u>dunes only</u>
wbuffer –	Includes long-term erosion and the factor of safety for potential erosion from a block failure (e.g. sudden large cliff failure) for <u>cliffs only</u>

Sea level rise scenarios (Section 4.1), note these eustatic values were modified for vertical land motion:
ec – Existing conditions (2010 water level)
s1 – Low sea level rise (27 cm by 2100)
s2 – Medium sea level rise (78 cm by 2100)
s3 – High sea level rise (153 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) is named:

“dhz_longterm_s22100.shp”

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, and the County of Santa Barbara (the “funding agencies”). The data and report do not necessarily represent the views of the funding agencies, their 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 have 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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The data are provided "as is" without any representations or warranties as to their accuracy, completeness, performance, merchantability, or fitness for a particular purpose. Data are based on model simulations, which are subject to revisions and updates and do not take into account many variables that could have substantial effects on erosion, flood extent and depth. Real world results will differ from results shown in the data. Site-specific evaluations may be needed to confirm/verify information presented in this dataset. This work shall not be used to assess actual coastal hazards, insurance requirements or property values, and specifically shall not be used in lieu of Flood insurance Studies and Flood Insurance Rate Maps issued by FEMA.

The entire risk associated with use of the study results is assumed by the user. The County of Santa Barbara, ESA and all of the funders shall not be responsible or liable for any loss or damage of any sort incurred in connection with the use of the report or data.

4. DATA SETS

4.1 Planning Horizons and Sea Level Rise Projections

The planning horizons (2030, 2060, and 2100) were selected based on input received during the County led stakeholder process and are consistent with the recent guidance document from the California Coastal Commission (CCC, 2015). The sea level rise scenarios used in this project are based on the recent study by the National Research Council (NRC, 2012) and consistent with the State guidance (OPC, 2013). The CCC (2015) guidance recommends using the range of projections and a medium scenario. Given the tectonic complexity of this region, additional effort was made to adjust for local vertical land motion.

The medium sea level rise scenario used the Los Angeles regional “Projection” and the low and high values were based on the ranges associated with NRC 2012 Table 5.3. Draft sea level rise policy guidance from the California Coastal Commission (CCC, 2015) recommends using the regional values reported in NRC 2012 and provides polynomial fit functions for projecting SLR for the Low and High curves (equations B3 and B4 in CCC 2015 Appendix B: Developing Local Hazard Conditions). Since NRC 2012 provides sea level rise amounts relative to 2000, rather than 2010 (the starting year for this study), sea level rise was assumed to be zero for the 2010 existing conditions. No adjustments were made for times later than 2010, which follows CCC 2015 guidance. The eustatic (no vertical land motion) NRC values for sea level rise at each planning horizon are shown in Table 1 and all SLR curves used in this study are presented in Figure 11.

Table 1. Sea level rise projections from NRC (2012), for the Los Angeles region, eustatic (without vertical land motion)

Year	*Low SLR*	*Medium SLR*	*High SLR*
2030	0.1 cm (0.04 inches)	9 cm (3.5 inches)	26 cm (10.2 inches)
2060	7 cm (2.8 inches)	30 cm (11.8 inches)	69 cm (27.2 inches)
2100	27 cm (10.6 inches)	78 cm (30.7 inches)	153 cm (60.2 inches)

Because of the complex geology and range of vertical land motion in Santa Barbara, ESA and the County and stakeholders agreed to remove the regional subsidence signal from the SLR curves and apply local uplift/subsidence rates. The rates of uplift were compiled from a variety of sources (Metcalf 1994, Trecker et al 1998, Keller et al 2000, Duvall et al 2004, Gurrolla et al 2014). Using the compiled rates from the scientific literature the coast was divided into 9 subregions with similar uplift rates. The uplift rates that were assigned to regions in the Santa Barbara County Study Area are shown in Figure 12. These values were used to reduce the relative sea level rise below the eustatic value based on NRC (2012). The regional subsidence value from Table 5.3 of NRC 2012 was added to three basins (not shown), increasing the relative sea level rise. The three sea level rise scenarios used in this study are defined as High, Medium and Low:

High Scenario

The intent of the high scenario was to assess a conservative "worst case scenario of sea level rise," and no uplift was subtracted but rather the NRC values (Table 5.3) for Los Angeles were used without regional subsidence. Therefore, the high scenario utilizes the eustatic projection of 1.53 m (5 ft) by 2100 for all areas except for three basins believed to be subsiding. The NRC regional subsidence value of 1.5 mm/yr was added for the three subsiding basins of: Goleta Slough, Santa Barbara waterfront, and Carpinteria Salt Marsh and adjacent areas.

Medium Scenario

We used the 78 cm (30.7 in) by 2100 eustatic projection then applied 9 local uplift rates (Figure 12) and the regional subsidence rate from NRC 2012 to the three subsiding basins.

Low Scenario

We used the 27 cm (10.6 in) by 2100 eustatic projection for Los Angeles (Table 5.3, NRC, 2012) without regional subsidence. We then applied the 9 subregion uplift rates (Figure 12) which lowered the relative sea level rise. Note that in some planning horizons, uplift reduced the amount of sea level to negligible rates. Any negative relative sea level rise calculated from the inclusion of uplift was set to zero. We also added subsidence for the three subsiding basins using NRC 2012 LA regional subsidence rate of 1.5 mm/yr.

4.2 Aerial Imagery

Digital Orthophotography

ESA downloaded the aerial mosaics from the NOAA Digital Coast Data Access Viewer (NOAA, 2012a). 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.

Oblique Aerial Imagery

ESA used the California Coastal Records Project website to identify coastal armoring and other relevant structures along the coast and to further assess the backshore characterization. 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

This study used the 2013 NOAA Coastal California TopoBathy Merge Project[4], which combined the sub-aerial 2009-2011 CA Coastal Conservancy DEM with nearshore jetski surveys and additional offshore bathy surveys. The dates associated with the 2009-2011 LiDAR were determined from the flightlines, which was important for updating the USGS historic cliff and sandy shore erosion rates.

2013 NOAA Coastal California TopoBathy Merge Project

Downloaded from the NOAA Digital Coast Data Access Viewer (NOAA, 2013), this merged DEM combined topographic, bathymetric and acoustic elevation data along the entire California coastline. The topographic LiDAR data set used in this merged project was from the 2009-2011 CA Coastal Conservancy LiDAR Project. The data were collected between October 2009 and August 2011[5]. This was the primary DEM used for conducting topographic analysis and mapping coastal erosion and flood hazard zones.

National Ocean Survey, N.O.A.A.

There are some nearshore gaps in the bathymetry data that had to be addressed for detailed wave run-up calculations. The primary data gap relevant to this study was along the coast near Carpinteria Salt Marsh. This data gap was filled with historic H-Sheet sounding data from 1979[6] that was converted to a bathymetric DEM.

4.4 Geology

Geologic maps were downloaded from two sources for the study area. GIS shapefiles for the Santa Barbara Coastal Plain Area were downloaded (Minor et al., 2009) and used along with georeferenced geologic maps of the remaining coastline (Dibblee, 1988a-d). Table 2 lists the geologic units and average erosion rates (computed from the USGS cliff erosion database updated with the 2009-2011 LiDAR cliff edge), Figure 12 shows the

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4 https://data.noaa.gov/dataset/2013-noaa-coastal-california-topobathy-merge-project-digital-elevation-model-dem

5 Additional metadata can be found at: http://www.ngdc.noaa.gov/docucomp/page?xml=NOAA/NESDIS/NGDC/MGG/Lidar/iso/xml/2013_CA_TopoBathy_m2612.xml&view=getDataView&header=none

6 Metadata found here: http://surveys.ngdc.noaa.gov/mgg/NOS/coast/H08001-H10000/H09752/GEODAS/H09752_h93.htm

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 Santa Barbara County

Geologic Unit	Description	Average Erosion Rate (m/yr)	Standard Deviation of Erosion Rates, Along Shore (m/yr)
Qa	Active channel alluvium	0.28	0.18
Qac	Alluvium and colluvium	0.05	0.02
Qca	Casitas Formation	0.15	0.12
Qcg	Conglomeratic unit	0.26	0.06
Qia	Intermediate alluvial deposits	0.06	0.06
Qmt	Marine-terrace deposits	0.22	0.24
Qoa	Older alluvial deposits	0.04	0.02
Qs	Beach sand	0.18	0.09
Qsb?	Santa Barbara Formation	0.13	0.11
Qss	Sandstone unit	0.26	0.11
QTst	Siltstone unit	0.43	0.16
Tm	Monterey Formation	0.19	0.1
Tmcg	Monterey Formation, conglomerate	0.21	0.13
Tml	Monterey Formation, lower calcareous unit	0.18	0.11
Tmm	Monterey Formation, middle shale unit	0.25	0.2
Tmu	Monterey Formation, upper siliceous unit	0.10	0.04
Tr	Rincon Shale	0.18	0.13
Tsq	Sisquoc Formation	0.18	0.1
Tu	Unnamed mudstone	0.23	0.09

4.5 Tides

The Santa Barbara tide gauge (NOAA #9411340) tidal datum was selected because it is within the study area. 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) and the Extreme Monthly High Water (EMHW) was mapped for the tidal hazard zones (see Section 9.1). The Rincon Island tide gauge (NOAA #9411270) was selected to determine the 100-year water level for coastal storm flood hazard mapping (see Section 9.1). These tide levels are listed in Table 3 and both tide gauge locations are shown in Figure 13.

Table 3. Santa Barbara tidal water levels

Tide	meters, NAVD88	feet, NAVD88
100-year High Water Level*	2.48	8.13
Highest Observed Water Level (Jan 27, 1983)	2.21	7.25
Extreme Monthly High Water**	1.99	6.53
Mean Higher High Water	1.61	5.28
Mean High Water	1.38	4.53
Mean Tide Level	0.82	2.69
Mean Sea Level	0.81	2.66
Mean Low Water	0.26	0.85
NAVD88	0	0
Mean Lower Low Water	-0.04	-0.13
Lowest Observed Water Level	-0.92	-3.02

Notes: The tidal datum analysis period was 1983 - 2001 at National Oceanic and Atmospheric Administration stations #9411340 and #9411270; NAVD88 = North American Vertical Datum of 1988. Sources: Tidal Datums (NOAA, 2005b)
* from NOAA Tides & Currents "Exceedance Probability Levels and Tidal Datums," for the Rincon Island tide gauge available at http://tidesandcurrents.noaa.gov/est/est_station.shtml?stnid=9411270. Accessed 9/3/2014.
** Extreme Monthly High Water was calculated by averaging the maximum monthly high water for all monthly data available at the Santa Barbara tide gauge (138 months).

4.6 Waves and Water Levels

Regional Wave and Water Level Data

Two sets of regional wave and water level data were used:

- Buoy and tide gauge data ("real" measured data); and,
- Model output data ("synthetic" model output).

These data were compared and each was used to develop nearshore wave data for input to the coastal erosion model and flood calculations (Section 6). The real data were used for the high scenario and the synthetic data were used for the medium and low scenarios.

Real Buoy Data: The 24-year offshore wave time series (October 1991 – October 2014) from 64-bin directional wave spectra (wave height, period, and direction) was developed using data from the CDIP Harvest buoy (CDIP #071) with data gaps filled with the CDIP Diablo Canyon buoy (CDIP #076). Older data from the Harvest Platform spatial array were processed but not used owing to apparent directional aliasing (an error in the distribution of wave energy over direction, which is not yet resolved by the providers of these data). The Harvest-Diablo Canyon time series was used to develop nearshore wave data for input to the coastal erosion model (Section 6) under the High sea level rise scenario. The highest resolution directional spectra (known as "64-bin") were used. See Figure 13 for the wave gauge locations.

Real Water Level Data: Historic tide water levels from the Santa Barbara tide gauge (NOAA #9411340) from 1996 to 2013 were used. These observations include "non-tidal residuals" (NTRs) that occur due to meteorological and climatic conditions. Since these same meteorological and climatic conditions affect waves, the wave and water level conditions are not completely independent. In fact, the worst coastal hazards are associated with coincident occurrences of high waves and high NTRs, and the effect on coastal hazard responses, such as total water level, are not necessarily linear (FEMA, 2005; Garrity et al, 2006).

Synthetic Buoy Data: ESA worked with USGS staff to incorporate the wave climate output from their Global Climate Models consistent with the CoSMoS methodology under refinement. Future projected wave data at a standard offshore output location (called "NAWC33" – see Figure 13 for location) were used for the Medium and Low SLR scenario hazard modeling. These data were found to be similar to the real wave data and discussions with USGS indicated this finding to be consistent with their research, which indicates that the highest 1% waves may come from a more westerly direction with more intense global warming (e.g. RCP8.5). However, the values available for this study were from the more moderate RCP4.5, often considered more similar to the B2 "mid-range" climate scenario. Owing to computational and memory demands, wave spectra were not available and only parameters were used (significant wave height, peak spectral period, and peak direction). A cumulative distribution comparison of the significant wave height (Hs), peak spectral period (Tp), and peak spectral direction (Dp) for real data from the Harvest buoy (CDIP Station 071) and synthetic data from global model GFDL-ESM2M for climate scenario RCP4.5, provided by the USGS (labeled NAWC33), are shown in Figure 14. The left panel shows the synthetic data for the period 2013-2030 compared with the real data from 1991-2014: The synthetic historical projection was not available at the time of the study. The right panel shows cumulative distributions of the NAWC33 data broken up by planning horizon. A comparison of the real and synthetic wave roses (plots of wave direction and height frequency of occurrence) is shown in Figure 15. See Figure 13 for the location of NAWC33 and the Harvest Buoy (CDIP station 071).

Synthetic Water Levels: The USGS provided synthetic water level non-tidal residuals (NTRs) that were coincident in generation with the synthetic wave data. These provisional data did not include all non-tidal residual constituents but did provide coincident timing that is important to the analyses. As a work-around, ESA bias-corrected the data by "stretching" the tail of the NTR distribution to match the long-term Los Angeles tide gauge data. Synthetic water level non-tidal residuals (NTRs) from climate modeling were compared with real data from tide gauges at Santa Barbara (closest), Los Angeles (longest but south of SB) and San Luis Obispo (north and next longest). In Figure 16, the probability density distributions (PDFs) show that the climate model output compares favorably with Santa Barbara in terms of the mean being positive. In Figure 17, the cumulative distribution is used to show the higher values (tail) of the synthetic distribution are smaller than the real data. Also shown in Figure 17 is the adjusted synthetic distribution with the tail amplified to match the Los Angeles data. The adjusted synthetic NTR data were added to projected astronomic tides based on publicly available software called Xtide (a tool from the model Ttide)[7] and used with the synthetic waves.

[7] http://www.flaterco.com/xtide/ last visited June, 2015.

Wave Transformation Models

The wave model was setup using two nested grids to develop wave transformation matrices for 17 locations; each called a model output point (MOP), along the Santa Barbara study area. The computational wave grid can be seen in Figure 13 along with input data sources and the MOP locations. Coordinates and descriptions of the chosen MOP locations are given in Table 4 below. An example of wave refraction output from the SWAN model is shown in Figure 18.

Table 4. Locations of MOP points within Santa Barbara County study area

ID	Easting UTM Z11 (meters)	Northing UTM Z11 (meters)	Note
1	179148.86	3821385.91	open coast Tarantulas wave focusing
2	186832.20	3816811.56	Cojo-Bixby Ranch refraction shadow
3	198799.88	3818441.65	Razors wave focusing (submarine canyon)
4	201566.33	3818419.82	wave shadowing at Gaviota
5	208080.04	3818545.66	outside of Gaviota wave shadow
6	216516.42	3817150.52	waves along Refugio coast
7	222220.97	3816871.82	wave shadowing at El Capitan
8	228041.91	3814189.33	wave focusing at Naples
9	230952.12	3813485.89	wave shadowing at Bacara
10	235532.32	3810589.93	wave focusing at Devereux
11	240351.74	3812379.05	wave shadowing at Goleta Beach
12	247107.61	3811029.62	wave focusing at Arroyo Burro
13	251011.41	3808779.39	focusing at Leadbetter Point
14	255484.39	3810965.74	wave shadowing at Santa Barbara waterfront
15	257392.81	3810946.54	wave focusing at Hammond
16	263490.19	3810132.71	wave shadowing at Padaro Lane (surf spot Loon Point)
17	266328.17	3808275.61	applied to wider range (Rincon) to account for modeling wave height overestimation at Carpinteria

The wave refraction by ESA was tested by comparison to real data output at several locations for selected conditions that were expected to challenge wave transformations. Based on this analysis, which was accomplished in concert with Li Erikson of the USGS, the wave grid was extended into north Santa Barbara County to better represent the effect of bathymetry on west-northwesterly waves refracting and diffracting into the Santa Barbara Channel. Also, the SWAN refraction model accuracy was diminished for the south-southeast wave directions based on testing with the historic 2014 Hurricane Marie swells: Data and observations show that larger wave penetration from the eastern openings to the Santa Barbara Channel occurred than is predicted by the modeling. However, no further adjustments to wave modeling were needed because there is insufficient buoy data to systematically adjust for these conditions with high confidence, and the primary westerly exposure was adequate for the purposes of the study. A future study should investigate locally generated south-southeast wind waves along the large fetch from Santa Monica Bay, and the potential for future tropical storm impacts.

Testing was also done to compare different representations of deep water wave data and different transformation methods. It was determined that use of the highest resolution direction spectra (called 64 bin), versus the progressively less detailed 9-band and peak parameter representations) were best suited for time series generation. Also, the method of using wave transformation matrices and matrix-multiplication proved to be essentially as accurate as full spectral refraction and was computationally much more efficient. Finally, use of peak spectral parameters was adequate for extreme large swells used for storm responses, either with parameterized spectra or matrix transformations. Consequently, ESA used the matrix multiplication method with the highest resolution spectra, which was 64-bin for real data and spectral parameters for synthetic data.

The wave transformation matrixes for the 17 MOP points (as well as the nearshore buoy test locations) consisted of refraction height ratios and local wave direction azimuths. Conceptually, a nearshore direction spectrum is computed by matrix multiplication of the offshore directional spectrum with the height matrix, with substitution of the offshore direction with the computed nearshore direction for each bin. The matrixes were computed for 43 bins of deep water directions at 5 degree intervals in the exposure direction range from 150 to 360 degrees, and 64 wave frequency[8] bins from 0.025 to 0.100 Hz (40 to 10 second periods) in 0.005 Hz increments, and to 0.58 Hz (~ 2 seconds) in 0.01 Hz increments. Each bin was modeled using a unit wave spectrum in SWAN, with spectral width adjusted based on peak period: Narrow spectral peaks were used for longer periods in order to represent the coherence of swell relative to shorter period seas.

4.7 Historic Shoreline Positions

USGS National Assessment of Shoreline Change for Sandy Shorelines

This California wide USGS assessment calculated short- (1970s to 1998) and long-term (1870s to 1998) shoreline change rates for sandy shorelines along the California Coast (Hapke et al 2006) and was downloaded from the USGS website (http://pubs.usgs.gov/of/2006/1251/). The report includes a GIS database containing three 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. Section 5.2 discusses how these erosion rates were updated with the 2009-2011 LiDAR dataset.

USGS National Assessment of Cliff Erosion

This California wide USGS assessment calculated long-term cliff edge erosion rates (end point rate between 1930s and 1998) along the California Coast (Hapke and Reid 2007) and was downloaded from the USGS website (http://pubs.usgs.gov/of/2007/1112/). The report includes a GIS database containing two historic cliff edges and other GIS files used to calculate the rates of change. The annualized retreat rate uncertainty for California cliff edges was reported at 0.2 m/year,

[8] Wave frequency (in hertz, Hz) is the inverse of wave period (seconds), which is proportional to wave length.

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

The coastal armoring database (J. Dare, 2005) was based on interpretation of oblique aerial photography from the California Coastal Records Project (www.californiacoastline.org). The dataset provides offset reference line representing the observable coastal armoring structures. The polyline layer of coastal armoring was used to determine along shore extents of coastal armoring.

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 digital elevation model described in Section 4.3 at 1 meter point spacing. These profiles were then analyzed in station-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 and DEM hillshade 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 were computed from the USGS 2006 National Assessment of Shoreline Change[9] updated with a 2009 MHW shoreline extracted from the 2009-2011 LiDAR as well as 18 additional shorelines from the PhD dissertation of Dave Revell (Revell, 2007) dating from 1938 to 2005 and spanning the coast from Isla Vista to south of Rincon Point. Cliff erosion rates were also computed from the USGS assessment updated with the digitized cliff edge from the 2009-2011 LiDAR dataset. Linear regression rates for shorelines and cliffs were measured at 100 meter spacing along-shore and compiled. Cliff erosion rates were checked against erosion rates from local studies covering most of the County coastline west of Santa Barbara Harbor (Deiner, 2000) and near the Carpinteria Salt Marsh. The updated USGS historic rates for sandy

[9] GIS shorelines available at; http://pubs.usgs.gov/of/2006/1251/#gis.

shoreline and cliff erosion along Santa Barbara County are presented in Figure 19 & Figure 20, respectively.

From the updated USGS erosion rates analyses, the linear regression rate (LRR, the rate computed from more than two cliff edges) was used as the primary erosion rate. There are data gaps in the USGS geodatabase for cliff erosion, so the longest end point rate (EPR, computed from two cliff edges) was used when the LRR could not be calculated. For shoreline erosion (at dunes and inlets), long term rates were used west of the Santa Barbara Harbor. Short term erosion rates were used east of the Santa Barbara harbor to remove the artifact of harbor dredging on shoreline position, since dredging management practices have largely stabilized since the mid-1970s. Because the beaches in Santa Barbara oscillate with large storms and Pacific Decadal Oscillation cycles, we assumed that any accretion rates (negative erosion rates) are a short term oscillation and not indicative of a long term trend: All historic accretion rates were set to zero (neither eroding nor accreting) for baseline conditions.

6. BACKSHORE CHARACTERIZATION

ESA used a backshore characterization scheme that follows previous studies conducted for the Pacific Institute, Monterey Bay and Ventura County (ESA 2014; 2013; Revell et al 2011; PWA 2009). An offshore baseline (smoothed line buffered (offset) seaward from the current shoreline) was divided into units based on backshore type (dune, inlet, or cliff), armoring, and geology. The baseline units were then segmented at 500 meter (~1500 feet) spacing (“Blocks”) to conduct the coastal modeling at a scale appropriate to decision making. The datasets described in Section 4 and the results from the topographic analysis (Section 5) were summarized into each of these alongshore blocks (296 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 9, below).

7. WAVE MODELING AND RUN-UP CALCULATIONS

7.1 Nearshore Wave Transformation Modeling

The nearshore transformation matrices were used to transform the 24-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 run-up for each along-shore analysis block (Section 7.2).

This approach provides a reasonable approximation of wave propagation from the open ocean into the Santa Barbara coast by accurately transforming the powerful swells that are 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 Run-up Calculations and Total Water Level Curves

The total water level is a water elevation determined by the sum of tides, waves and wave run-up, and other components including nearshore currents, storm surge, and atmospheric forcing. As sea level rises, the relative amount of time that the water contacts the backshore will increase. This relative increase is the key driving factor forcing the backshore erosion model.

For each along-shore study block, the wave run-up 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 17 nearshore wave transformation points. Wave run-up was added to the ocean water levels. As described in Section 4.6, ocean water levels were derived from the Santa Barbara tide gauge (NOAA #9411340) from 1996 to 2013 for use with real wave data whereas synthetic water level data were constructed for use with synthetic wave conditions provided by the USGS. The ocean water levels were added to the computed run-up to produce a total water level (TWL) time series for each block. Sea level rise amounts were then added to these computed total water levels.

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 run-up 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 21.

The Stockdon run-up equation was developed for natural shores and includes wave setup and run-up. It is used as a first approximation for run-up but is replaced with a more accurate representation for steep backshores where inland extents of wave run-up are computed (Section 9.1 Wave Run-up).

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. This separation was provided 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 multiplied by the planning horizon to get the baseline erosion. 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.

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 2005a). The 100-year (0.01 annual recurrence probability) was computed by extrapolation with an extreme value distribution (Weibull) fitted to the computed total water level time series. The erosion extent was not limited by duration and may over-estimate the average erosion extent caused by a single event. However, the computed extent of erosion could be realized in a particular location and during an extreme winter with one or more clusters of extreme ocean conditions.

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 (offset) in ESRI's ArcGIS software with an ArcINFO® license. The reference line for the erosion hazard zone is the location of the crest 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 and dune face) 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 P_f and P_e 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 Western Santa Barbara County.

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 22). 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 run-up are reaching). The exponent, m, was kept at 0.5, in agreement with the previous studies.

Erosion Factor of Safety

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 cliff failure, a block failure distance was included in the erosion distances for each block as a second set of cliff erosion hazard zones, which is based on field observations for the respective geological units. This addresses the risk of localized block failures that would not be captured by long-term average erosion, especially in the near term. The following block failure widths were selected based on observed block failures from aerial imagery and digital terrain models,

For the majority of the study area:

- Existing Conditions – assumed a 5 meter block failure width.
- 2030, 2060, and 2100 – utilized one standard deviation of the historic erosion rate times the planning horizon (ranged from 0.01 to 0.23 meters/year)

For the Mesa/Hope Ranch cliff backed areas:

- All planning Horizons – used spatially varying geomorphic failure distance
  - Sea Ledge – assumed a 120 m block failure width.
  - Douglas Preserve – assumed a 50 meter block failure width.
  - Shoreline Park – assumed a 30 meter block failure width.

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 (offset) 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 edited for anomalies.

9. COASTAL FLOOD HAZARD ZONES

Three types of coastal flood zones were developed for this study: back beach flooding (lagoon flooding behind a built up beach berm), wave run-up (computed from maximum historic and projected wave conditions), and 100 year tidal flooding (generated in the two tidally open systems in the County: Santa Barbara Harbor and Carpinteria Salt Marsh). Not originally scoped, but also provided are the Extreme Monthly High Water levels mapped in SB Harbor and Carpinteria Salt Marsh and adjacent areas.

9.1 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 Santa Barbara study area. For this study, the shoreline was broken into regions based on the geomorphology and dominant process driving coastal flood levels (Figure 23). The following flood processes were considered:

- 100-year Tide
- Wave Run-up
- Beach Berm (seasonally closed lagoons)

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

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 23), e.g. Santa Barbara Harbor, Carpinteria Salt Marsh). 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, and especially important in low lying areas. In these areas a wave run-up analysis was conducted to estimate the limit of wave run-up on the profile.

Twenty five representative profiles were analyzed along the entire Santa Barbara County study area (Figure 24). The profiles are based on the topography and bathymetry datasets described in Section 4.3. Where no topography data was available in the surf zone, the profile was linearly interpolated between the bathymetry and topography limits, with the exception of the Carpinteria area that had large gaps that were filled with historic sounding data, described in Section 4.3. They reflect the wide range in topography and bathymetry across the Santa Barbara County study area.

The Stockdon run-up 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 run-up at every study block. These wave parameters (significant wave height, wave length, direction) were then used as inputs to a run-up 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 (previously 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 Iribarren 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 25. 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).

The program also uses the Direct Integration Method (DIM) to estimate the static and dynamic wave setup and resulting high dynamic water surface profile (FEMA 2005a; 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 run-up directly on barriers combine to form the highest total water level and define the flood risk (FEMA 2005a). 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 run-up. 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 inland extents were projected inland from the zero meter NAVD contour (reference elevation for composite slope run-up computations) to develop the flood hazard map for the regions where wave run-up was identified as the dominant flood hazard (Figure 23).

Seasonally Closed Lagoons (Bar Built Estuaries)

The Santa Barbara County shoreline 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 enough runoff fills the lagoon but does not breach it. 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 Santa Barbara shoreline (Figure 23). By using the spring 2009-2011 LiDAR combined with geomorphic assessment of sediment grain size characteristics, beach slopes and wave exposure, we estimated the maximum potential beach berm elevation that would back up lagoon waters and cause the highest flooding. We assumed that the maximum flood level would occur when the lagoon filled up to the beach berm just before spilling over and breaching (naturally), that is typical during rainfall events. These water levels are not associated with a return interval (e.g. 100-year) – this requires joint probability analysis of waves building up the beach with the timing/ magnitude/probability of large rainfall events, and is beyond the scope of this project.

Table 5. Geomorphically interpreted maximum berm crest elevations for seasonally closed lagoons – existing conditions

Name	"Maximum" Berm Crest *ft NAVD88*
Jalama Creek	13
Wood Canyon	11
Damsite Canyon	11
Canada del Cojo	11
Barranca Honda	11
unnamed lagoon	11
Arroyo el Bulito	11
Canada del Agua	11
Canada del Sacate	11
Canada de la Cuarta	11
unknown river	11
Canada del Agua Caliente	11
Canada de la Gaviota	11
Canada del Leon	11
Canada San Onofre	11
Arroyo Hondo	11
Arroyo Quemado	11
Tajiguas Creek	11
Canada del Refugio	11
Canada del Venadito	11
Canada del Corral	11
Canada del Capitan	11
Las Llagas Canyon	11
Dos Pueblos Canyon	11
Tecolote Canyon	12
Bell Canyon	12
Devereaux Slough	12
UCSB Lagoon	11
Goleta Slough	11
Arroyo Burro	11
Mission Creek	11
Sycamore Creek/Andree Clark Bird Refuge	11
Montecito Creek	11
Arroyo Paredon	11
Carpinteria Creek	11
Rincon Creek	11

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.

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. Wave run-up flood hazard areas are considered "connected" as the modeling results show that wave run-up can connect those low-lying areas to the ocean.

9.2 Rising Tides Hazard Zones

Extreme Monthly High Water (EMHW)

Though not originally scoped, we developed forecasts of flooding based on a more frequent water level elevation in response to stakeholder requests and the apparent usefulness of this information to local planning. The extreme monthly high water level (once per month, on average) was mapped (in addition to the 100-year tide) in the two open tidal systems Carpinteria and SB Harbor, considering existing EMHW and EMHW under future sea level rise (not considering storm events). Two types of 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.

The monthly Extreme Monthly High Water (EMHW) was estimated by averaging the maximum monthly water level for every month recorded at the Santa Barbara tide gauge (EMHW = 2.0 meters (6.6 ft) 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, and those areas with a direct connection with the ocean were labeled "connected" in the "Connection" attribute. The other low-lying areas were also included and were labeled "connection uncertain"[10]. The connectivity of these

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

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.

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.

10. FLUVIAL FLOODING

This study also modeled future conditions fluvial flooding on Carpinteria Creek. The fluvial analysis is divided into two primary components: (1) analysis of climate change data and impacts to extreme rainfall and flood conditions; and (2) hydraulic modeling of projected flood conditions. An ensemble of climate models was evaluated and high-emissions/high-risk and medium-emissions/medium-risk scenarios were selected from the range of the climate model projections to characterize possible future extreme streamflow events.

10.1 Climate Change Data Analysis

The goal of the climate change data analysis was to review existing climate model data to estimate changes in extreme rainfall and flood conditions. The changes in extreme flood conditions were used to drive the inflow boundary for the hydraulic and hydrodynamic models described in the next section.

Downscaled hydrology data for Carpinteria Creek was processed and distributions for the 100-year flowrate (Q100) from all downscaled model data from the CMIP5[11] data archive (http://gdo-dcp.ucllnl.org) were computed. ESA reviewed the full distribution of models and selected scenarios that reflect a risk associated with the SLR scenarios and planning horizons chosen for this study, shown in Table 6 and Figure 26.

Extreme streamflow analysis was conducted to estimate the change in 100-year discharge for 2030, 2060, and 2100 under a medium and high emissions scenario. Based on FEMA’s effective Flood Insurance Study (FIS) for Santa Barbara County, the 100-year discharges on Carpinteria Creek is 12,000 cfs (FEMA, 2005b). This value was used as the existing condition for hydraulic modeling of flood extents described in the next section.

[11] Coupled Model Intercomparison Project Phase 5 (CMIP5) using models developed for the International Panel on Climate Change (IPCC)’s fifth Assessment Report (AR5).

Table 6. Global climate model scenarios mapped to SLR modeling scenarios

SLR Scenario	Planning Horizons		
	2030	**2060**	**2100**
High	RCP[12] 8.5, 90th percentile	RCP 8.5, 90th percentile	RCP 8.5, 90th percentile
Medium	RCP 4.5, 50th percentile	RCP 4.5, 50th percentile	RCP 4.5, 90th percentile
Low	Existing Q100	Existing Q100	Existing Q100

10.2 Hydraulic Modeling Analysis

The hydraulic modeling assessment involved evaluating climate change impacts to flood levels using the existing one-dimensional (1D) HEC-RAS model originally provided by Avila and Associates (pers. comms., April 2015). It is a draft model that is pending FEMA approval. The model was updated by ESA for the future climate scenarios flood analysis. First the existing conditions model was run with the highest predicted flow and most extreme tail water (high SLR at 2100). Areas of over-bank flow were identified and cross sections were extended as needed to contain the flow within the model. Extended portions of cross sections sampled the 2009-2011 LiDAR data. The overbank flow path at Hwy 101 was neglected for this analysis because there are planned improvement projects for the Highway 101 Carpinteria Creek bridge to prevent flooding down Highway 101.[13] For the purpose of predicting flooding down the Carpinteria Creek Corridor, it is conservative to assume that there is no overbank flow at Highway 101; however, this assumption may underestimate the extent of flooding along the alternate Highway 101 flow path. The extents of the updated HEC-RAS model are shown in Figure 27.

Resulting changes in future discharge on Carpinteria Creek from the climate data analysis described above were added to the existing 100-year stream discharge for each scenario and planning horizon (Table 7). The downstream tail water boundary condition was set to the MHHW elevation from the Rincon tide gauge (NOAA #9411270) and lifted with sea level rise amounts for future conditions corresponding to the planning horizon and SLR scenario (Section 4.1). Results of flooding extents and depths corresponding to each modeling scenario were then mapped in ArcGIS using the HEC-GeoRAS utility.

[12] Representative Concentration Pathways (RCPs): RCP8.5 can be compared to the prior A1FI and A2 scenarios and is more severe than RCP 4.5 which can be compared to the B1 Scenario.

[13] This includes a project recently considered by the Carpinteria Creek Council: http://carpinteria.granicus.com/MetaViewer.php?view_id=2&clip_id=193&meta_id=15786

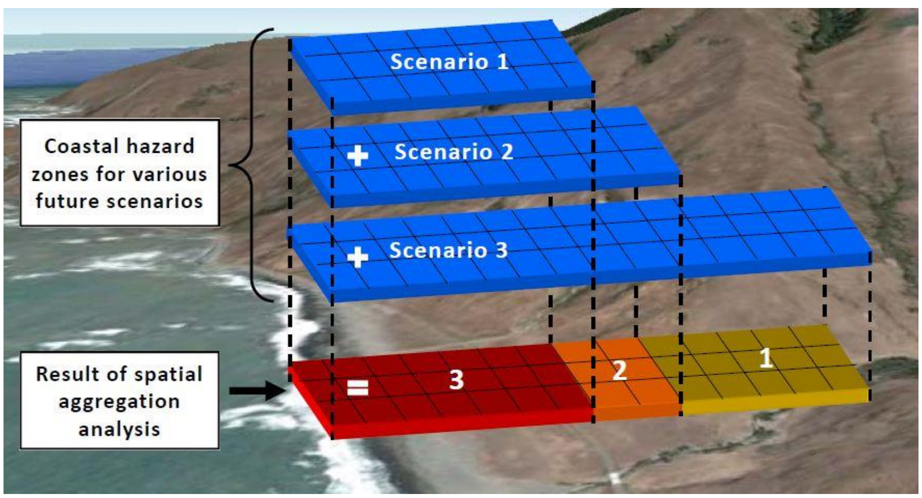
Table 7. Hydraulic model boundary conditions for each SLR scenario

Scenario	Discharge (CFS)	Tailwater (ft NAVD)
Existing Conditions	12000	5.36
2030 Low SLR	12000	5.36
2030 Medium SLR	14041	5.59
2030 High SLR	17971	6.24
2060 Low SLR	12000	5.69
2060 Medium SLR	14041	6.36
2060 High SLR	17971	7.92
2100 Low SLR	12000	6.22
2100 Medium SLR	14041	7.63
2100 High SLR	24571	10.37

11. ASSESSING A RANGE OF SCENARIOS

This study considered a range of future scenarios related to sea level rise, storm erosion, 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 on dune erosion, and with and without a factor of safety for block failures on cliff erosion. This process of overlaying and counting the number of overlapping hazards is called "spatial aggregation," and is shown in Figure 28. An example aggregated output is shown in Figure 10 (the example shows dune erosion hazard zones aggregated for the year 2100).

Figure 28 - 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 particular 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).

12. LIST OF PREPARERS

This report was prepared by James Jackson, P.E. (Hydrologist, Project Manager), James Gregory, P.E., and To Dang, Ph.D. with technical oversight by Bob Battalio, P.E. (Project Director). Additional support was provided by Dave Revell, Ph.D., Dane Behrens, Ph.D., P.E., Eddie Divita, P.E., Louis White, P.E. and Elena Vandebroek, P.E.

We acknowledge benefiting from work by others. We thank the US Geological Survey (USGS) and in particular Li Erikson. Steve Campbell of Campbell Geo, Inc. assisted with interpretation of vertical land motion. We also acknowledge our use of public resources such as LiDAR, bathymetry, wave and tidal data.

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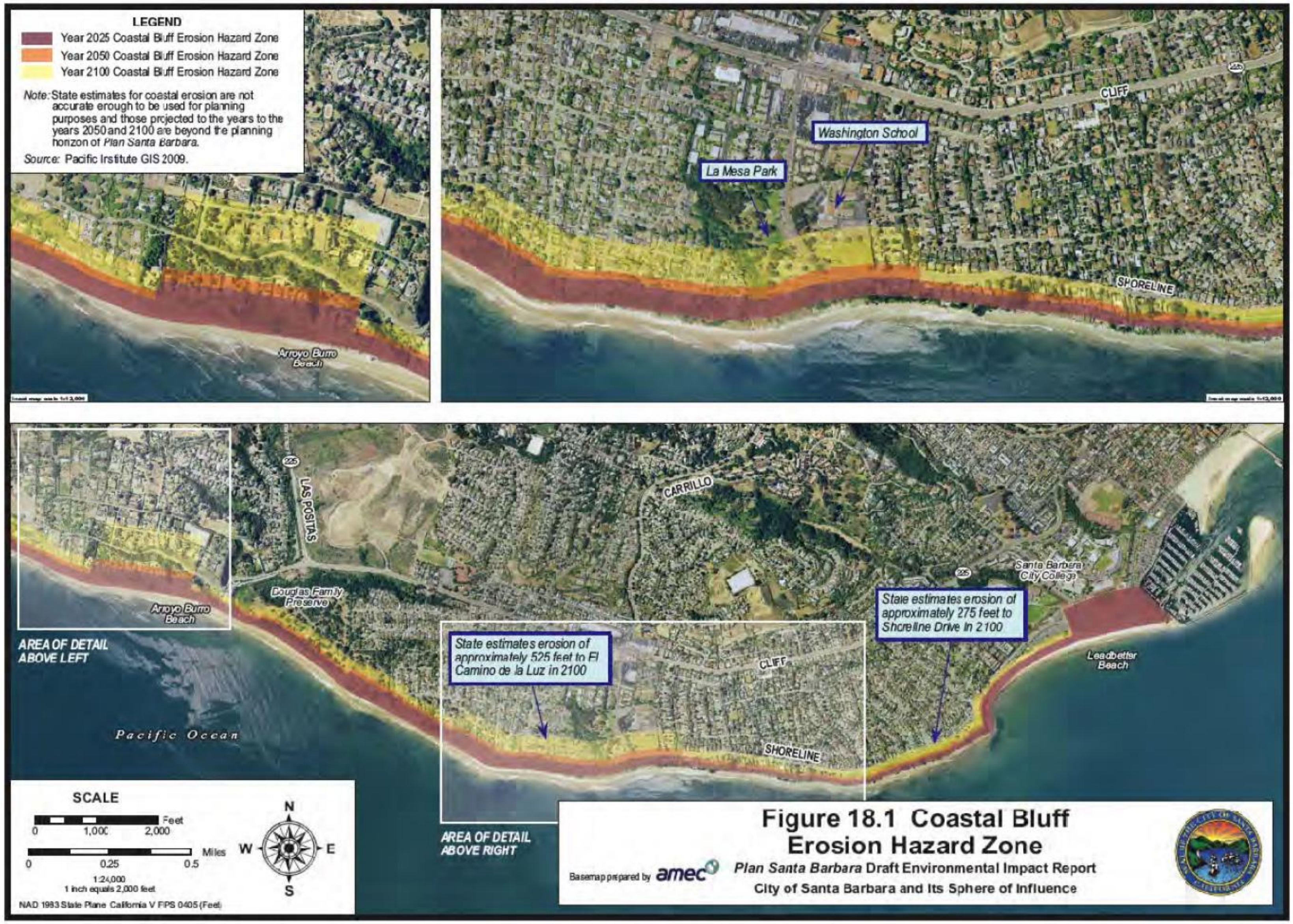
Figure 1

Santa Barbara County study area



SOURCE: AMEC, 2010

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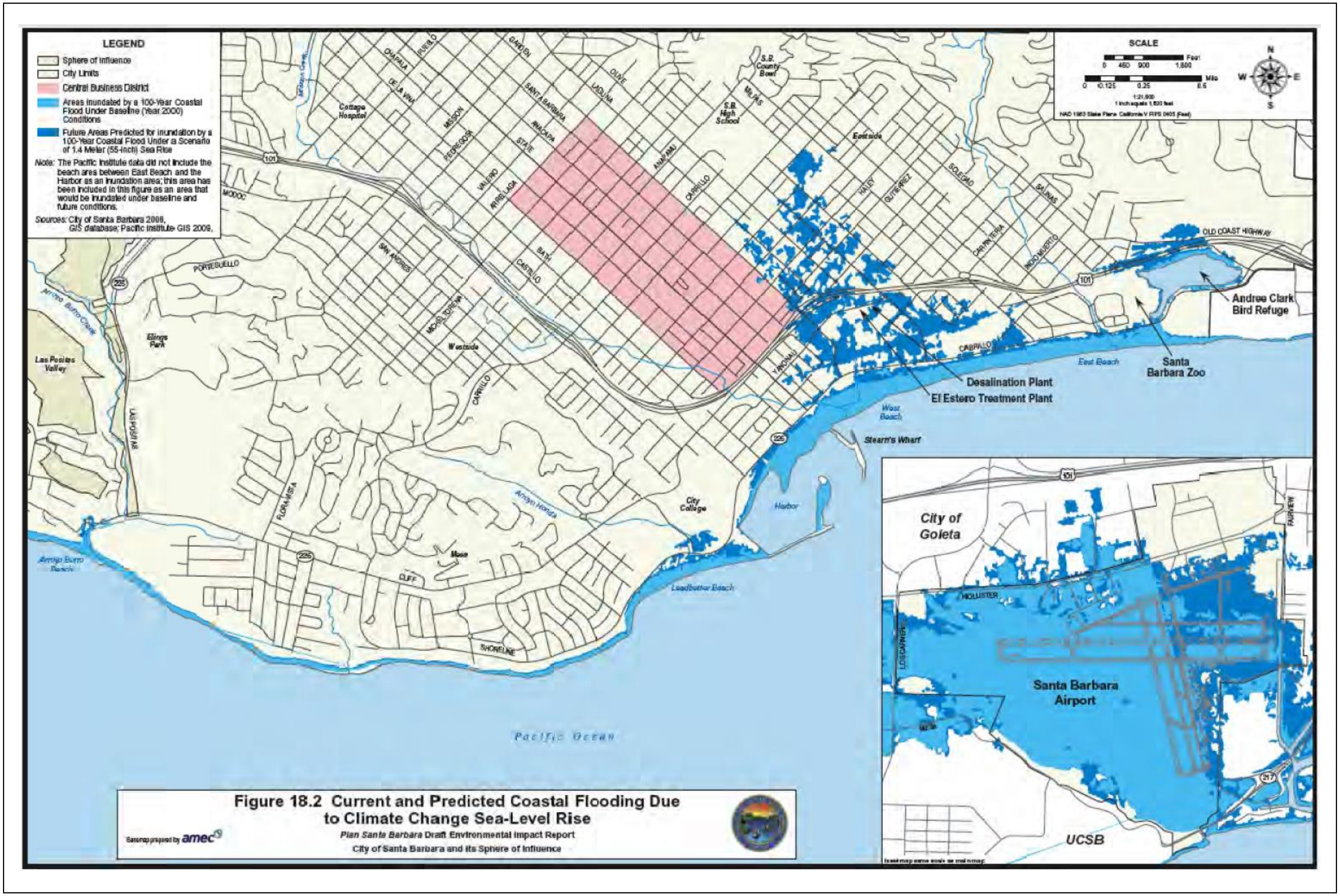
Figure 2

Coastal erosion hazards based on the Pacific Institute – PWA mapping



SOURCE: AMEC, 2012

Figure 3
Inundation map from the City of Santa Barbara General Plan Update EIR

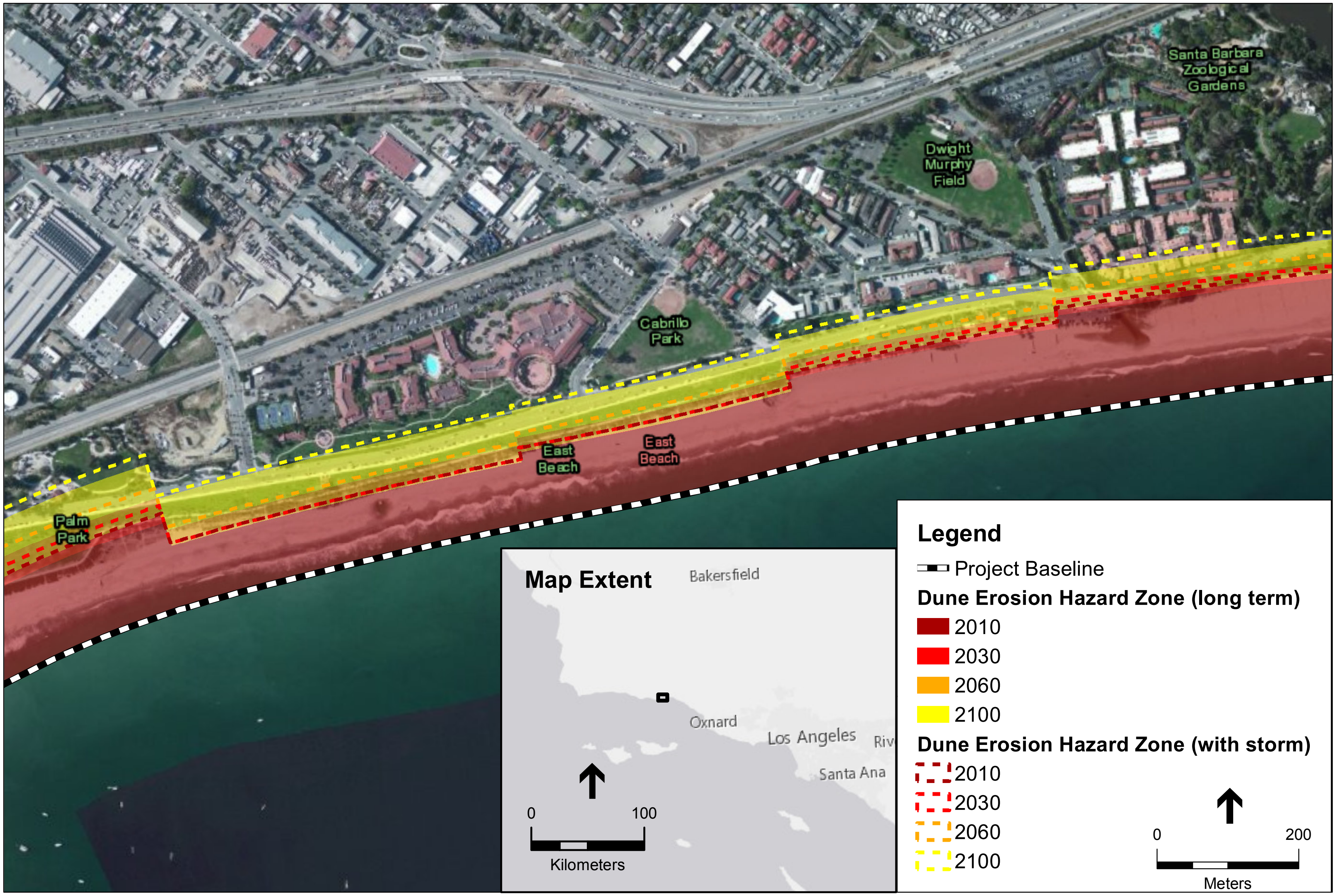


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Figure 4

Example of dune erosion hazard zones

NOTE: The hazards shown are for the "high sea level rise" scenario of 1.53 meters of SLR by 2100 relative to 2010. These hazard zones do not consider coastal armoring at this time.

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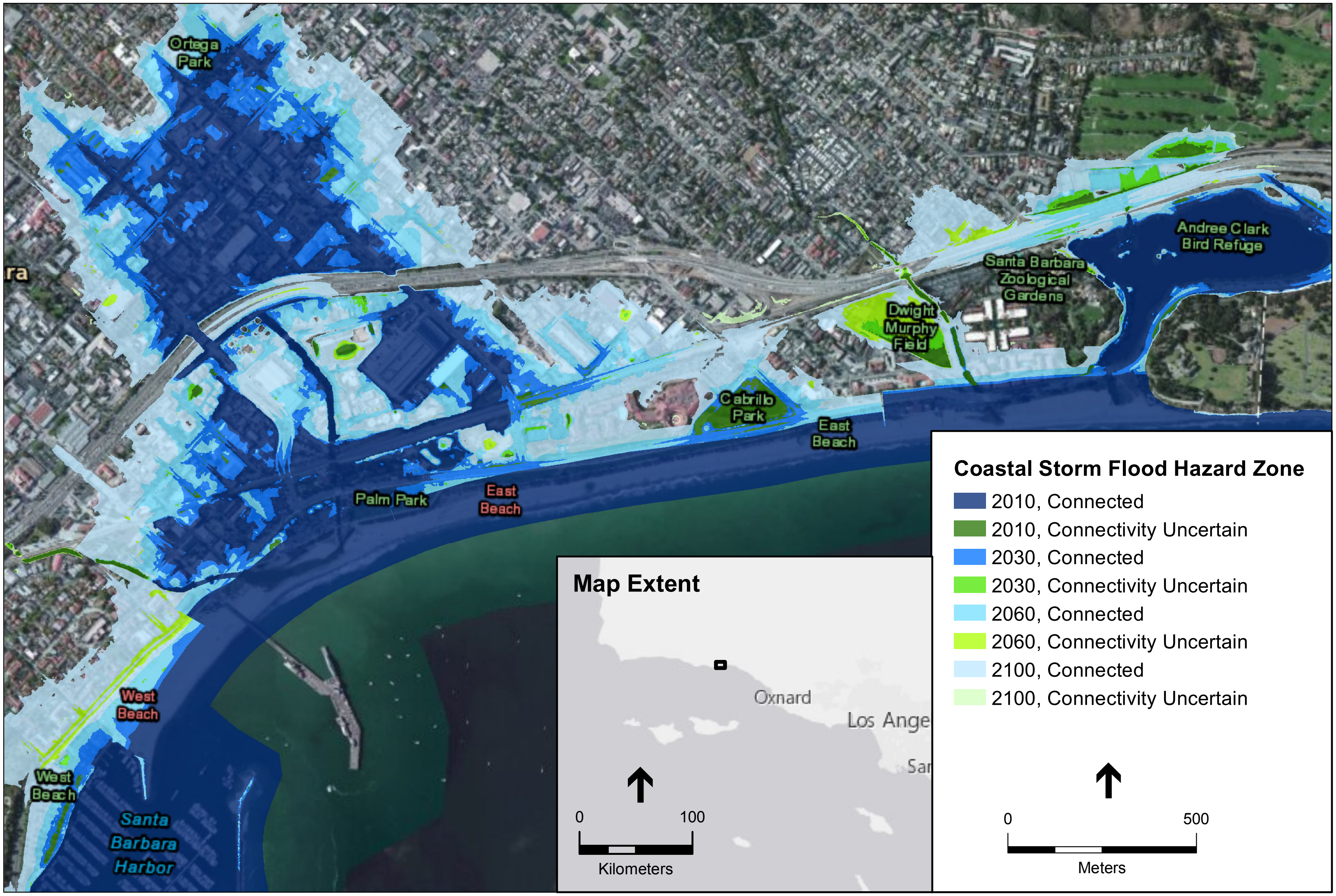
Figure 5

Example of cliff erosion hazard zones

NOTE: The hazards shown are for the "high sea level rise" scenario of 1.53 meters of SLR by 2100 relative to 2010. These hazard zones do not consider coastal armoring at this time.



NOTE These future tide inundation zones are for the "High" sea level rise scenario of 1.53 meters by 2100, relative to 2010.
Tide gates on the Laguna Channel and management of Mission Creek are not considered in this study.

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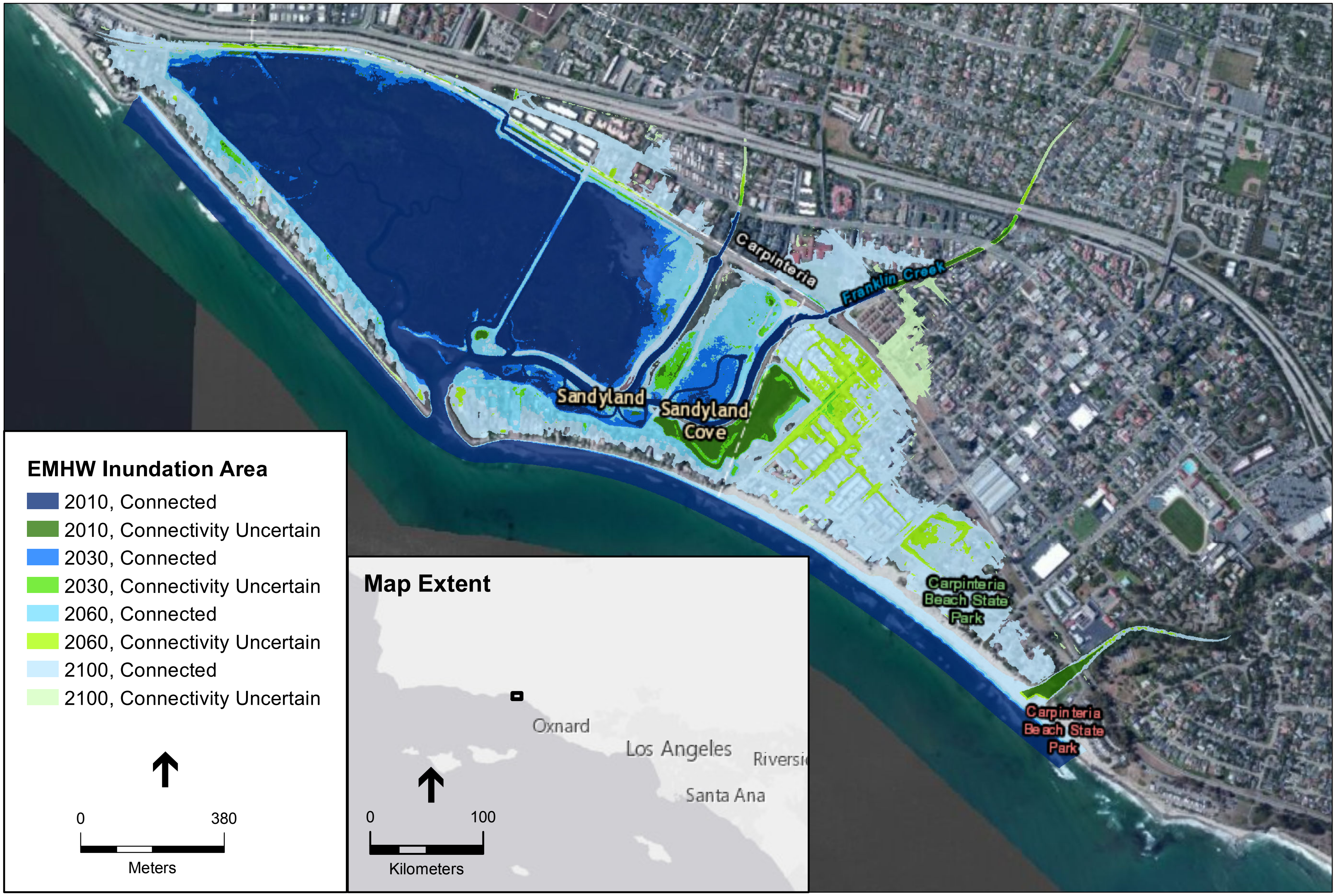
Figure 6
Example of coastal storm flood hazard zones



NOTES:
1. These future tide inundation zones are for the "High" sea level rise scenario of 1.53 meters by 2100, relative to 2010.
2. Assumes a monthly extreme water level of 1.99 m NAVD88 in 2010, as estimated by ESA.
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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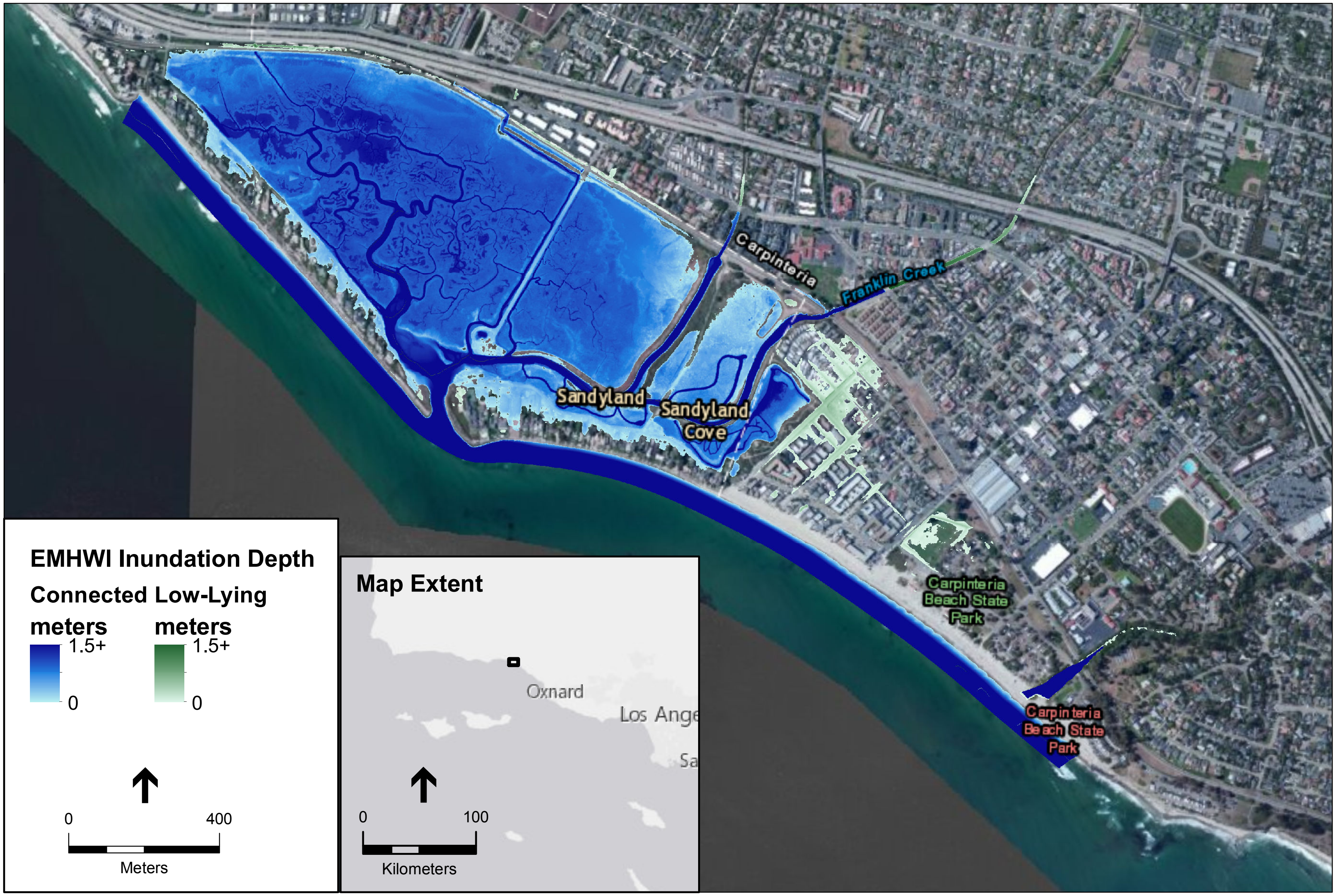
Figure 7
Example of extreme monthly tide inundation area



NOTES:
1. These future tide inundation zones are for the "High" sea level rise scenario of 1.53 meters by 2100, relative to 2010.
2. Assumes a monthly extreme water level of 1.99 m NAVD88 in 2010, as estimated by ESA.
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 8
Example of extreme monthly tide indation depth (2060)

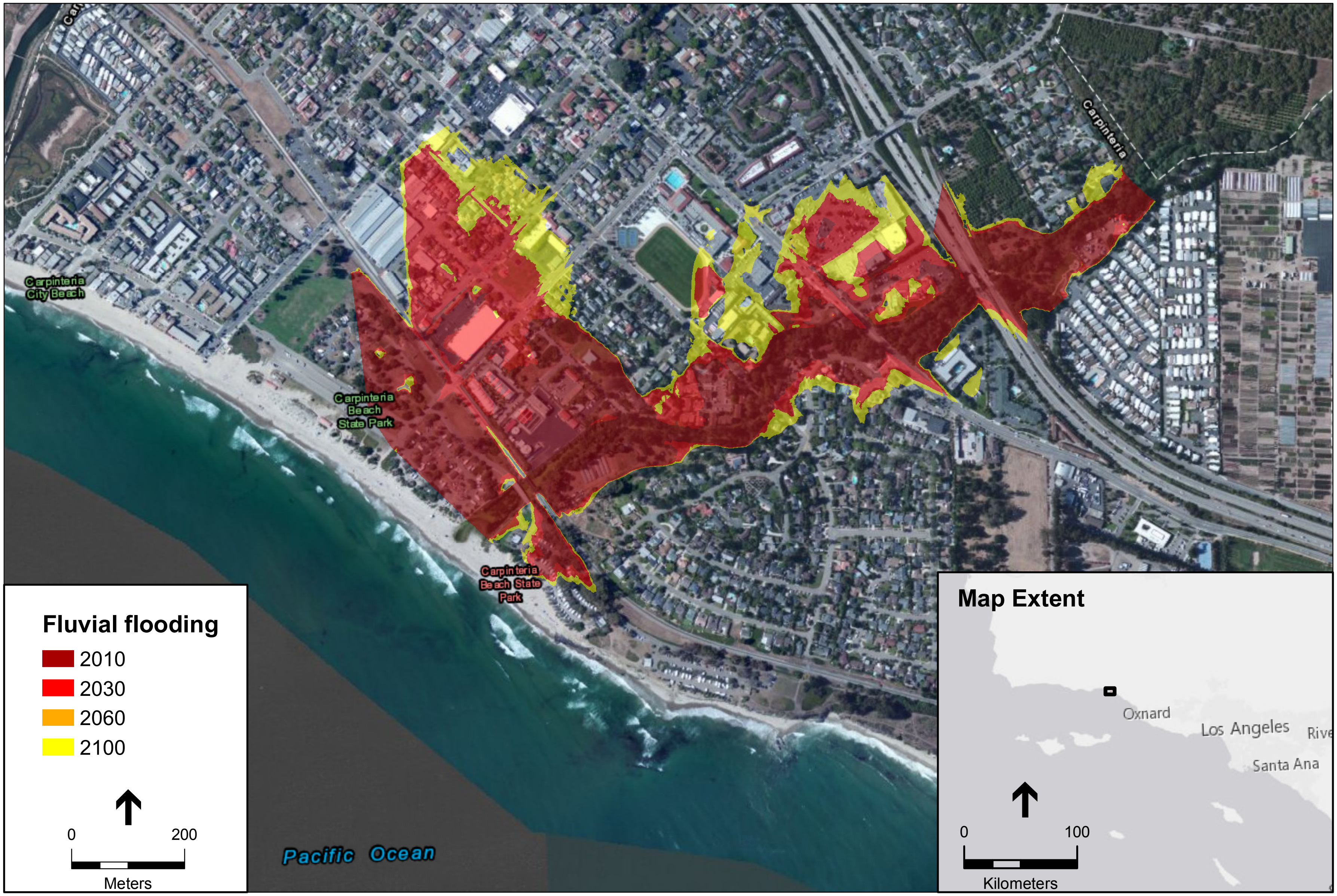

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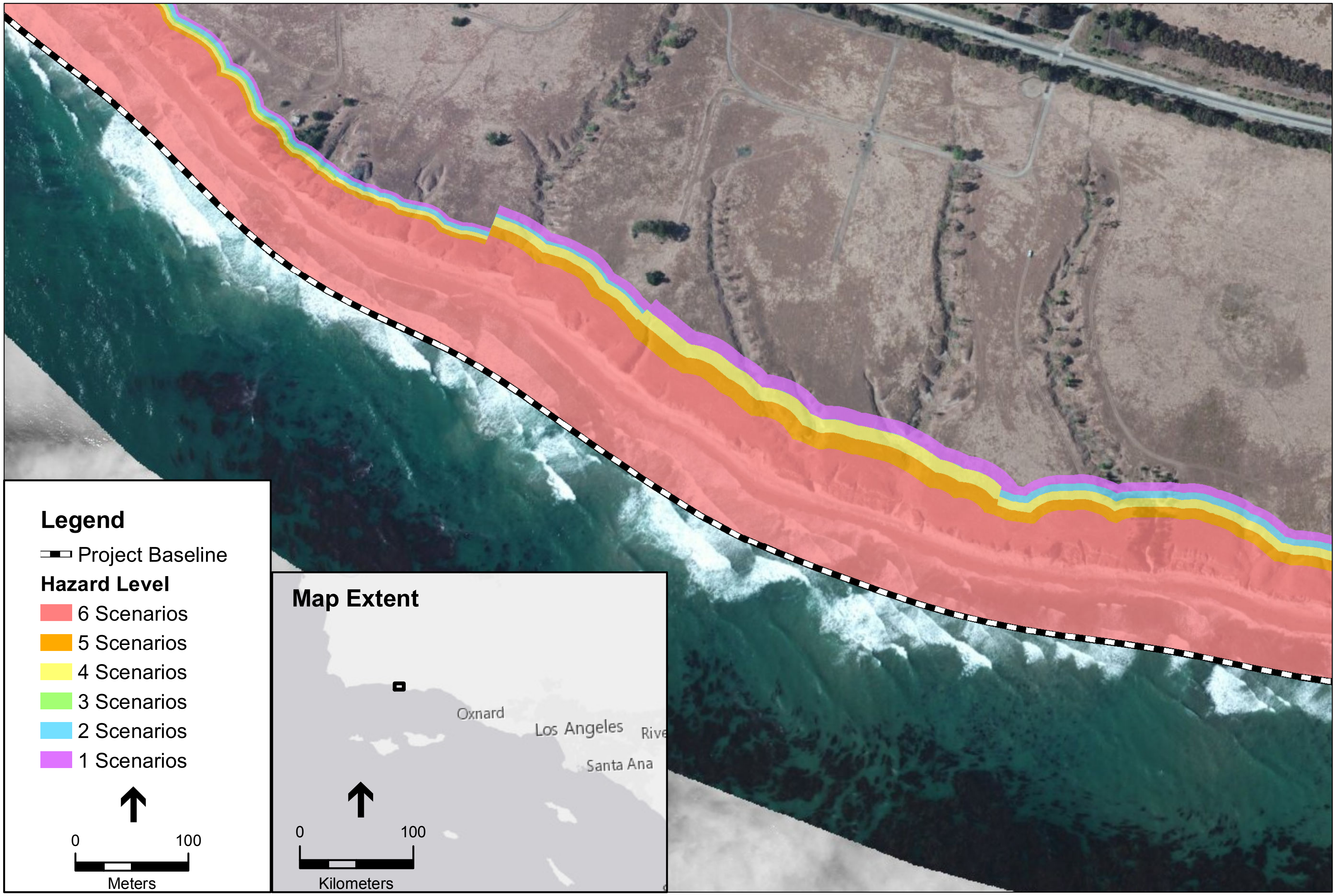
Figure 9

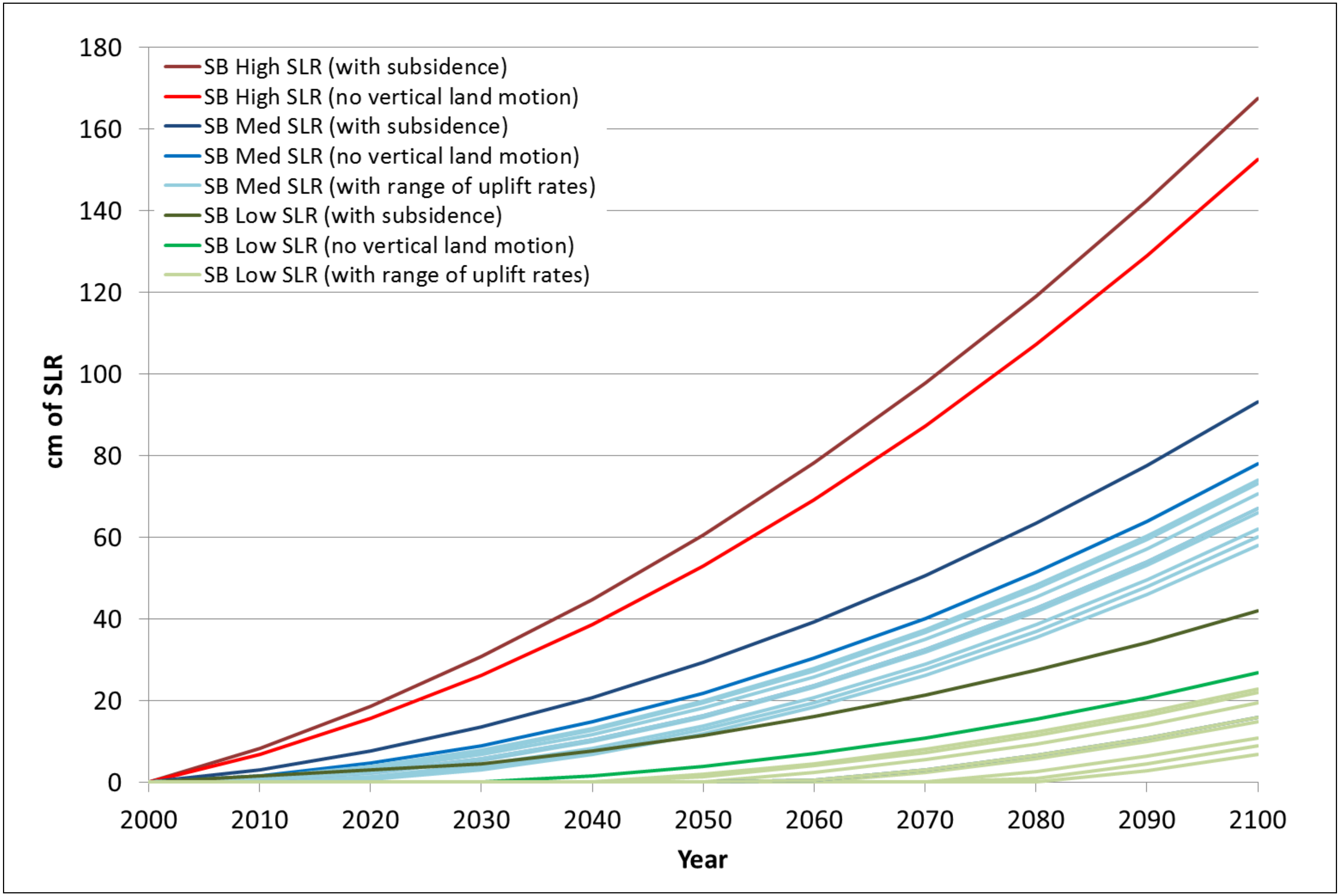
Fluvial flooding hazard zones

NOTE: The hazards shown are for the "high sea level rise" scenario of 1.53 meters of SLR by 2100 relative to 2010.



NOTE: The hazards shown are for the "high sea level rise" scenario of 1.53 meters of SLR by 2100 relative to 2010.

Figure 10
Example of spatial aggregation hazard zones



SOURCE: Table 5.3 NRC, 2012.

NOTE: Baseline eustatic curves (no vertical land motion) are the NRC LA Regional curves without regional subsidence for the Los Angeles Tide Gauge location, others with local uplift/subsidence added.

Figure 11

NRC sea level rise curves adapted to local uplift rates in Santa Barbara County

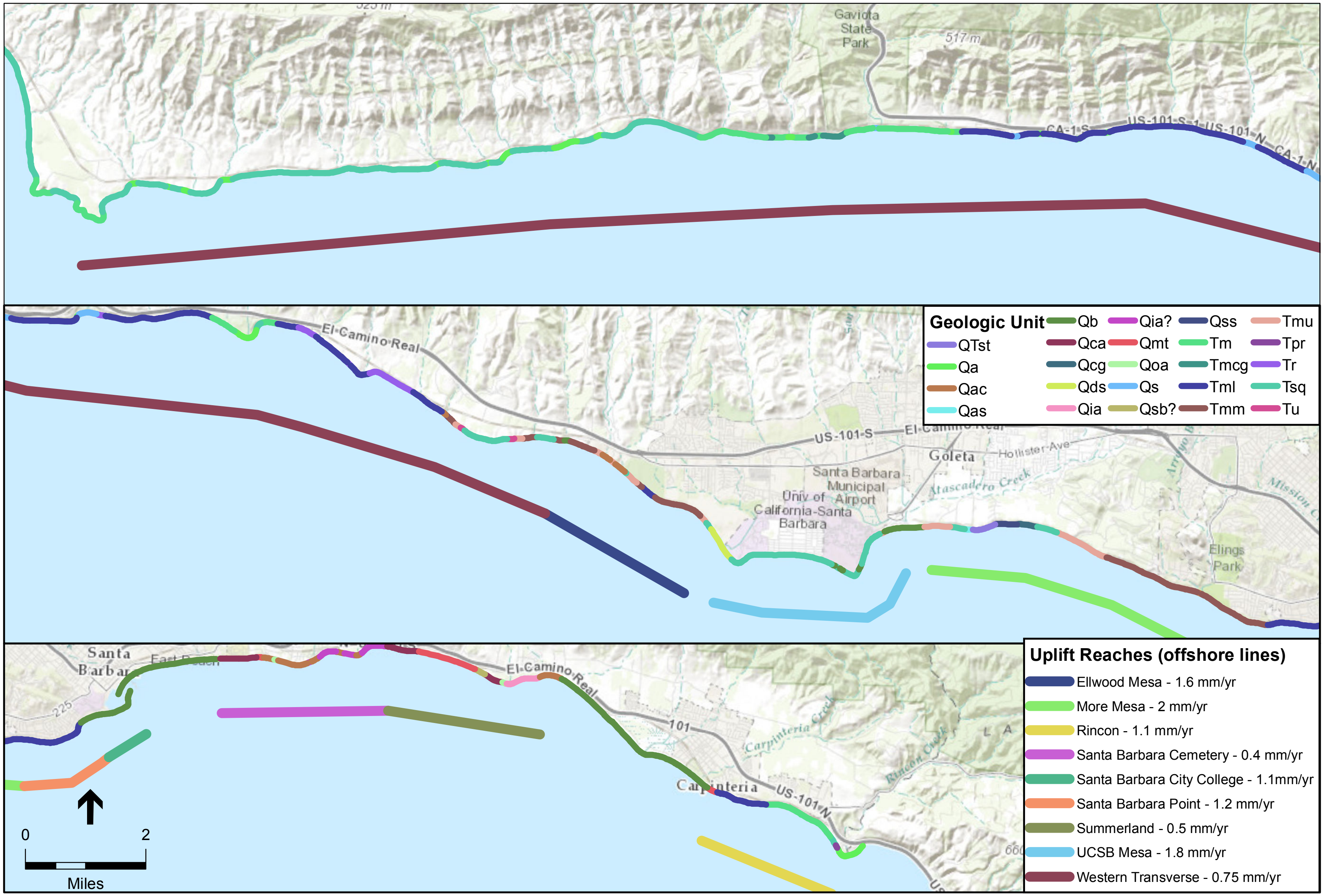
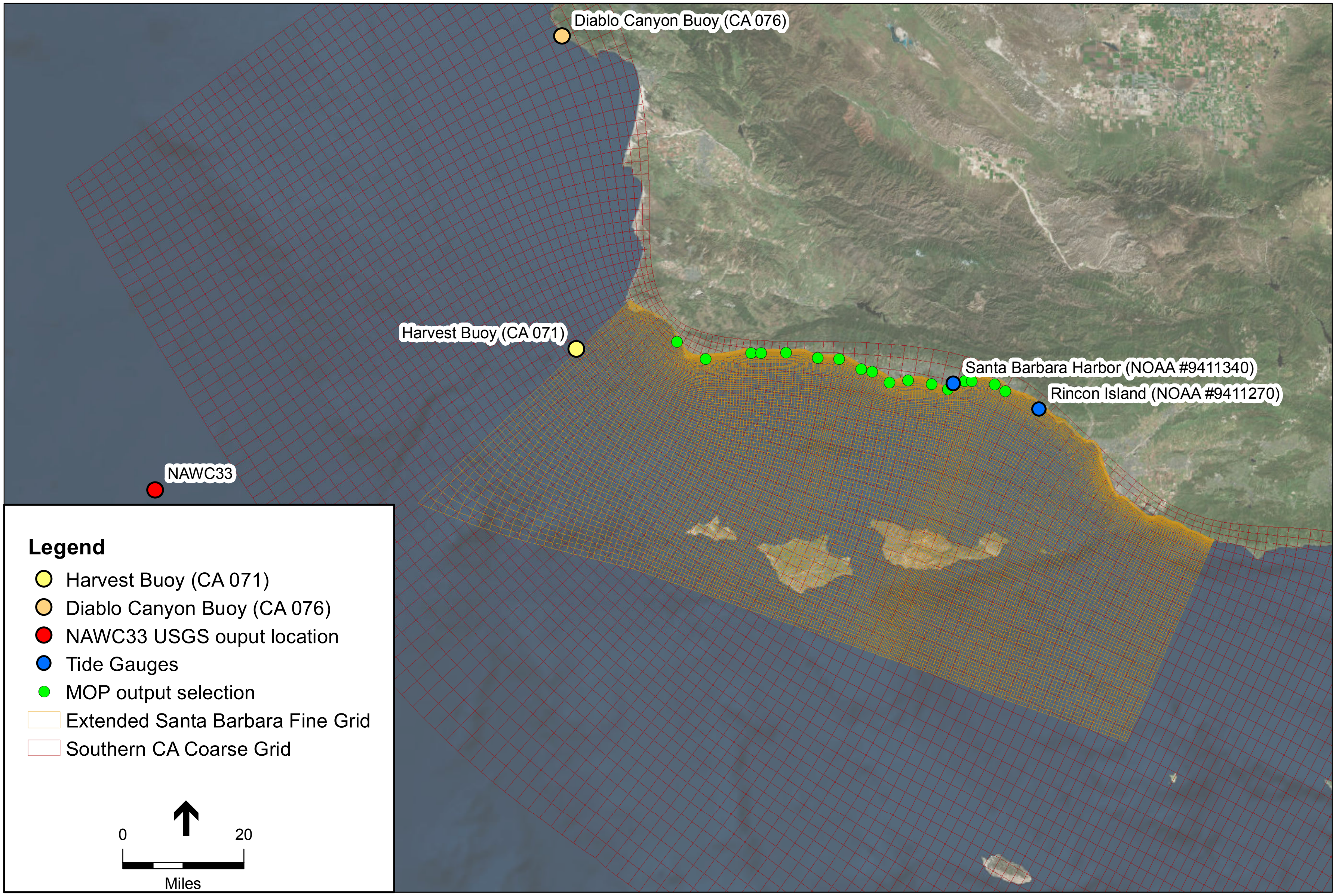


Figure 12

Coastal geology and uplift rates in Santa Barbara County



SOURCE: NOAA, 2015; USGS, 2015; ESA , 2015

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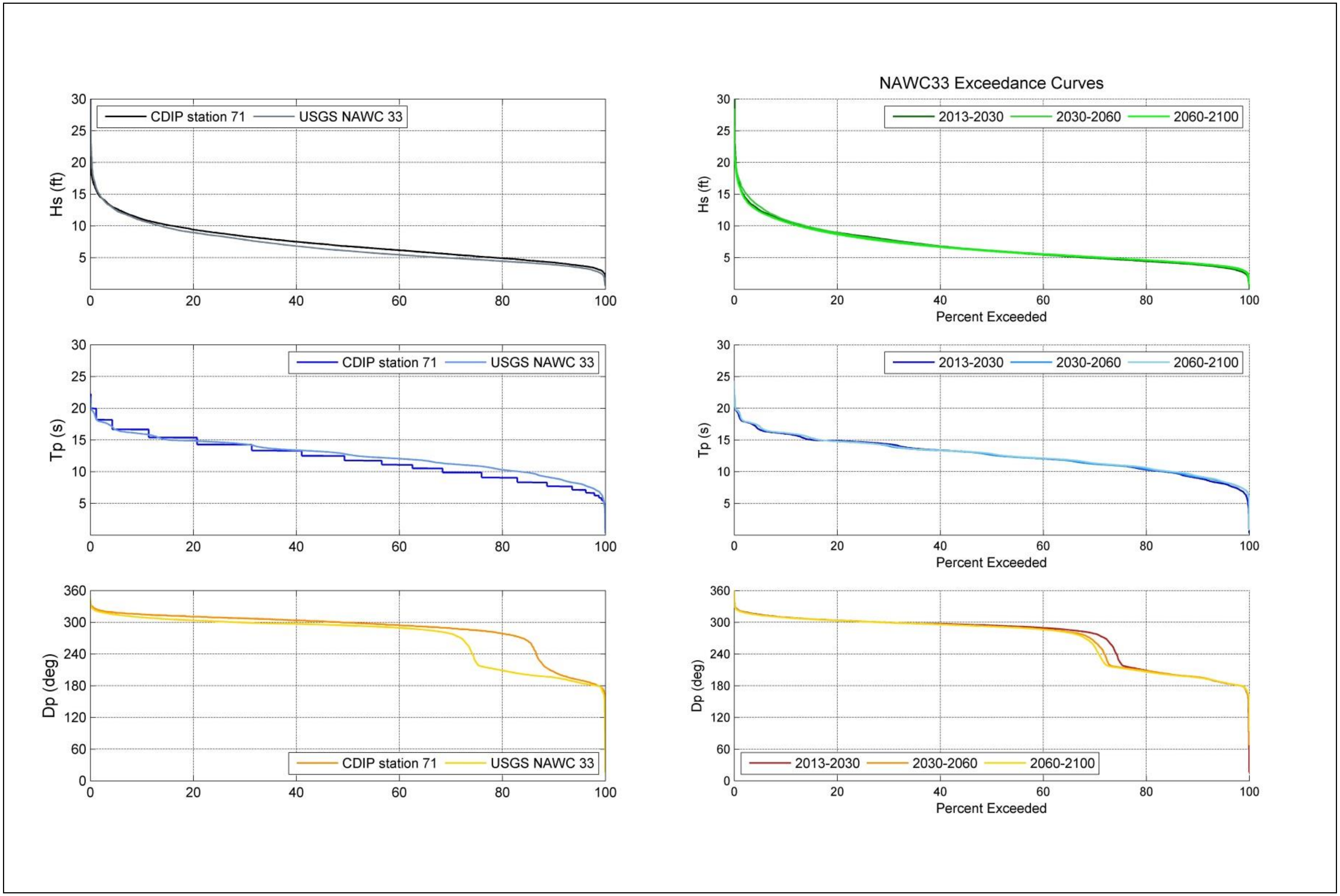
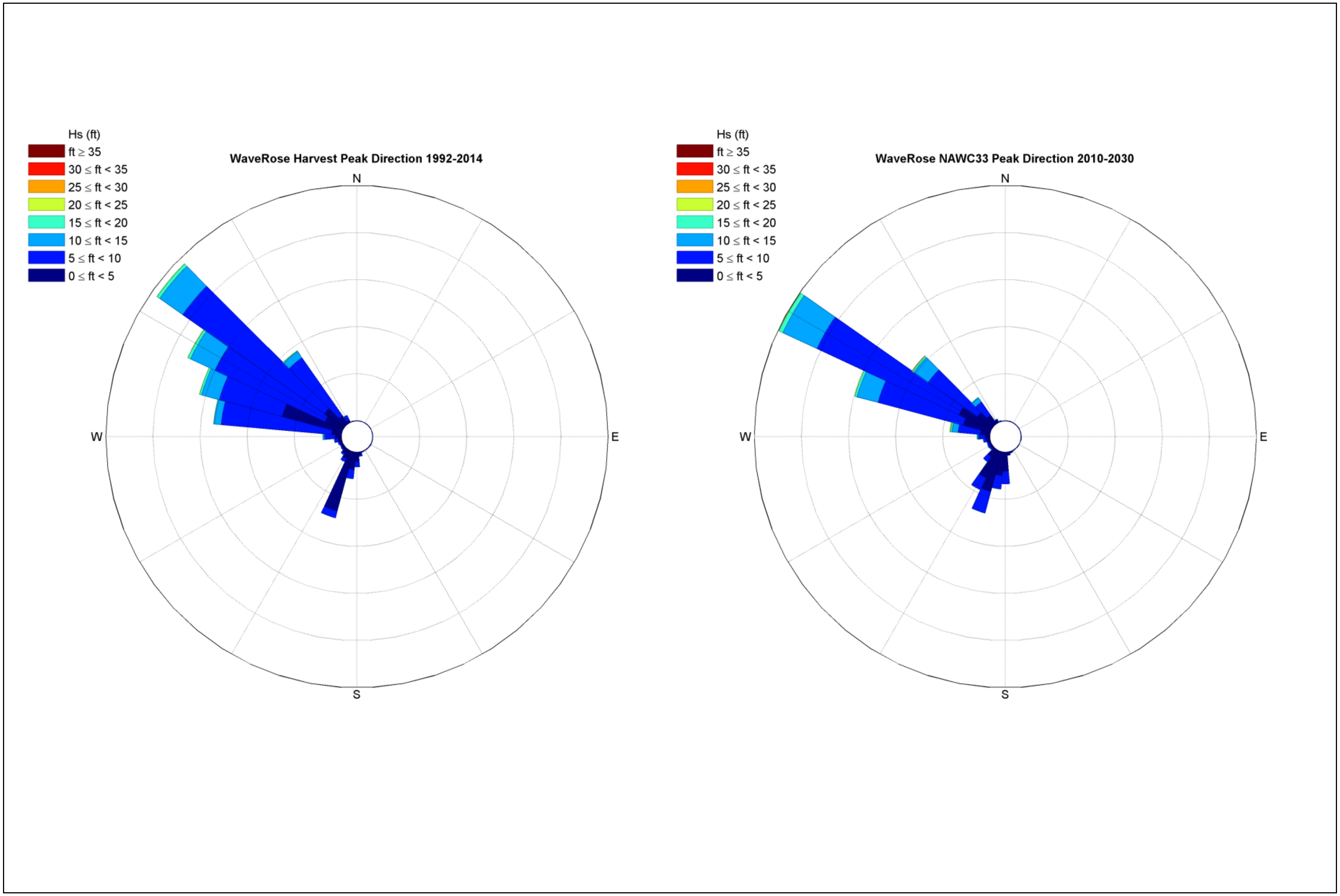
Figure 13
Wave modeling grids, buoys, tide gauges and MOP locations



SOURCE: NDBC, 2014; USGS, 2015.

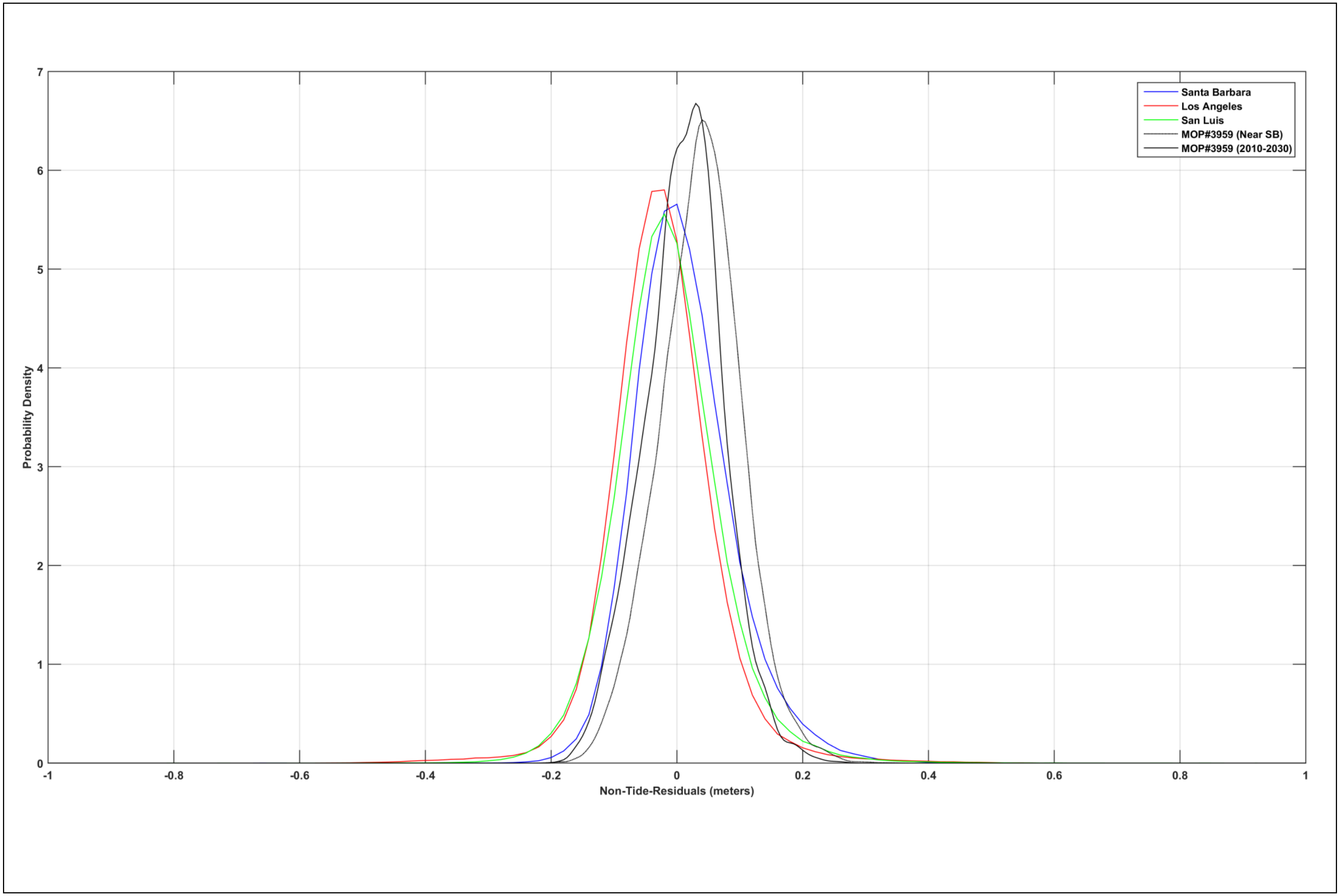
Figure 14

Cumulative distributions of wave parameters for Harvest gauge (real data) and GCM output (synthetic data from NAWC33)



SOURCE: NDBC, 2014; USGS, 2015.

Figure 15
Wave roses for the Harvest gauge (real data) and the GCM output (synthetic data, from NAWC33)

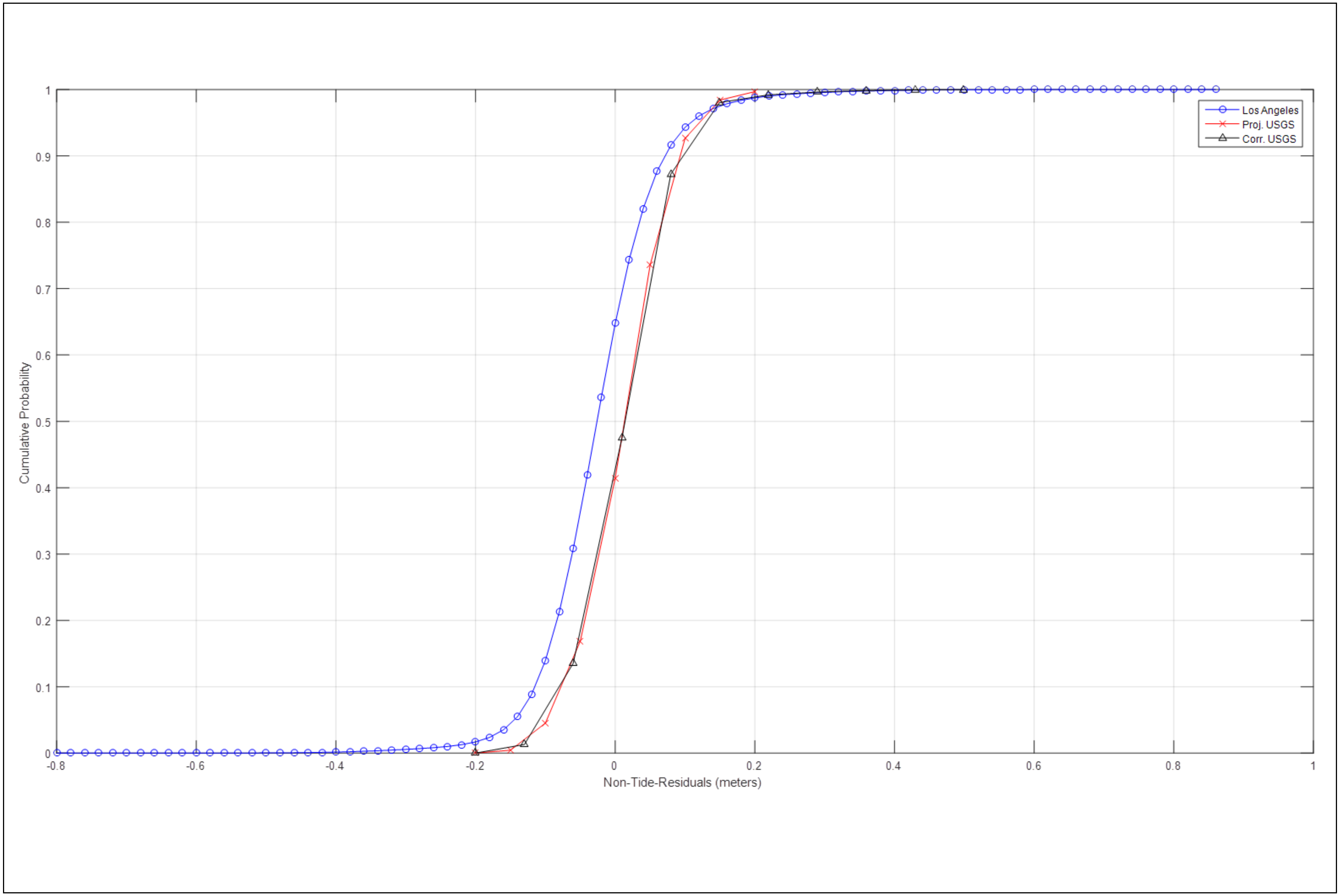


SOURCE: NDBC, 2014; USGS, 2015.

SB County Coastal Hazards Modeling . 130526.00

Figure 16

Synthetic water level non-tidal residuals from climate modeling compared with real data from tide gauges

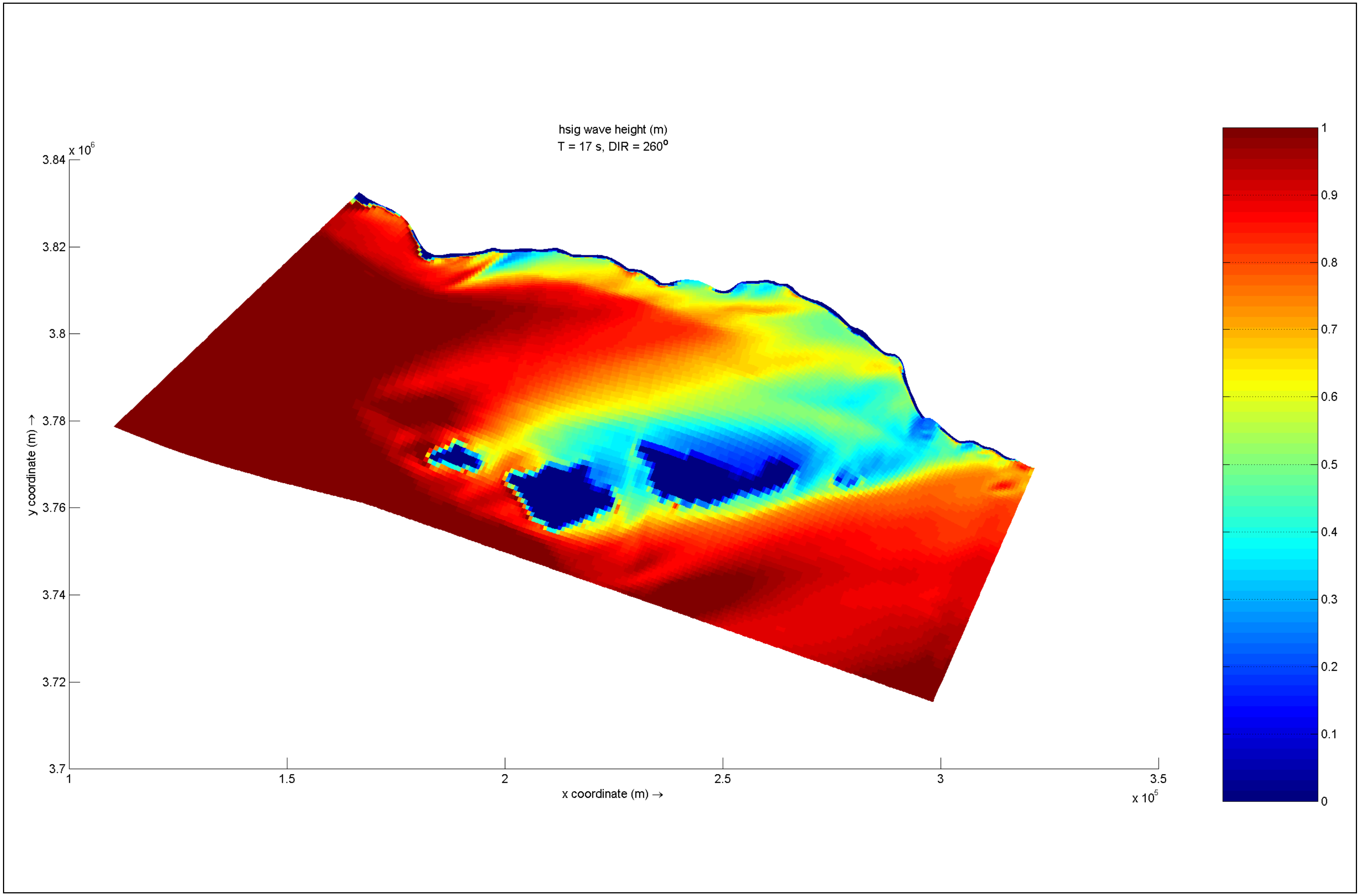


SOURCE: NDBC, 2014; USGS, 2015.

SB County Coastal Hazards Modeling . 130526.00

Figure 17

Synthetic water level non-tidal residuals adjusted to match LA historic extreme values

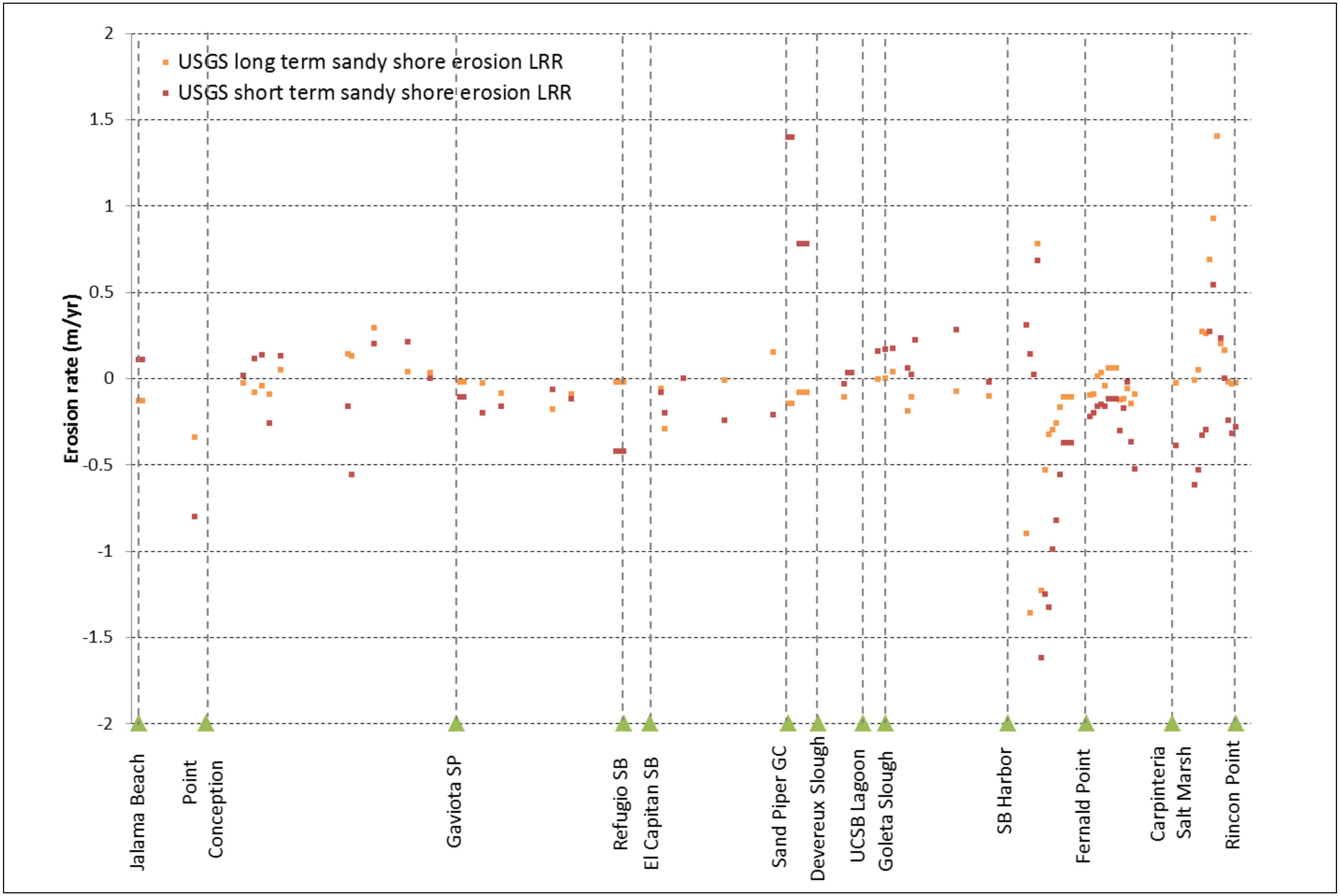


SOURCE: NDBC, 2014; USGS, 2015, ESA 2015.

SB County Coastal Hazards Modeling . 130526.00

Figure 18

Example wave refraction diagram from the SWAN model



NOTE: Negative erosion is accretion.

Figure 19

Historic sandy shoreline erosion rates in Santa Barbara County

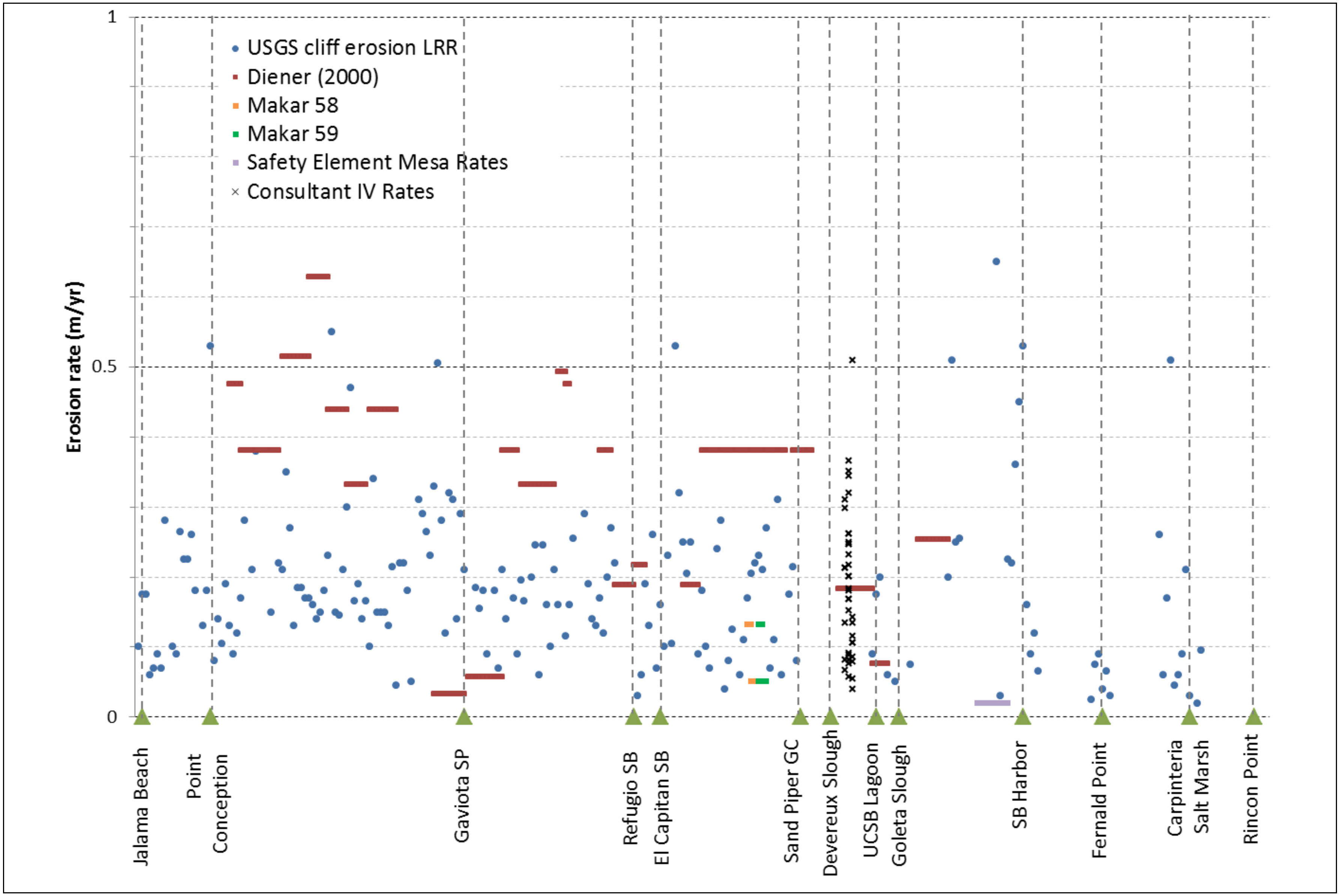
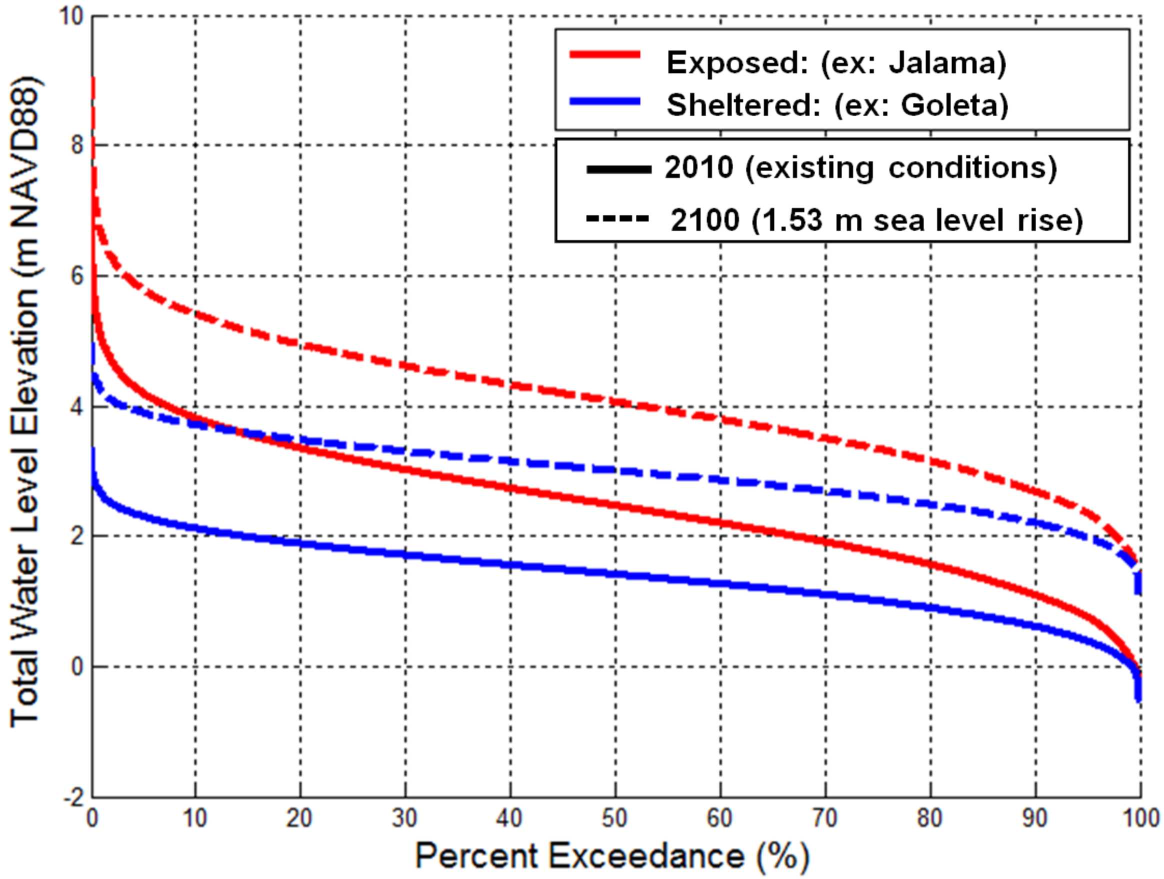


Figure 20

Historic cliff edge erosion rates in Santa Barbara County



SOURCE: ESA, 2015.

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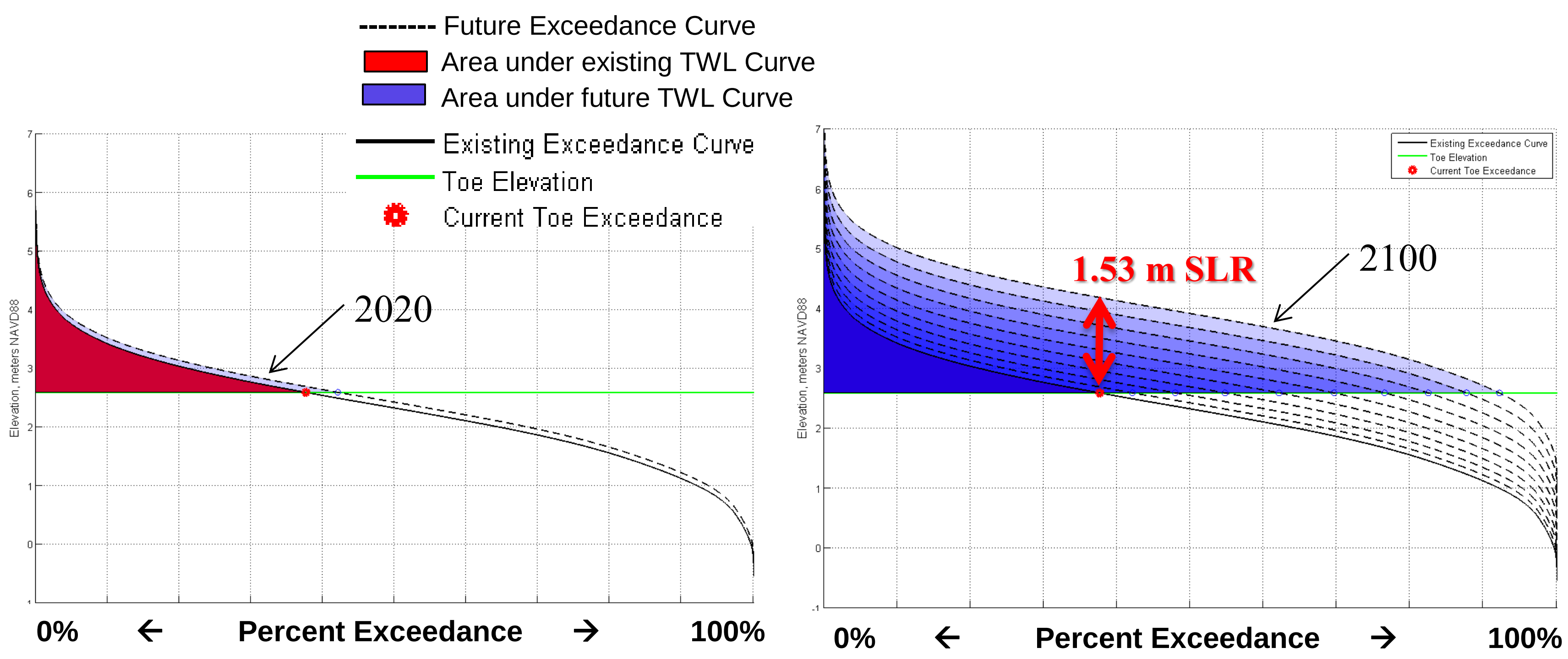
Figure 21

Example of total water level exceedance curves



SOURCE: ESA

Figure 22
Cliff erosion methods

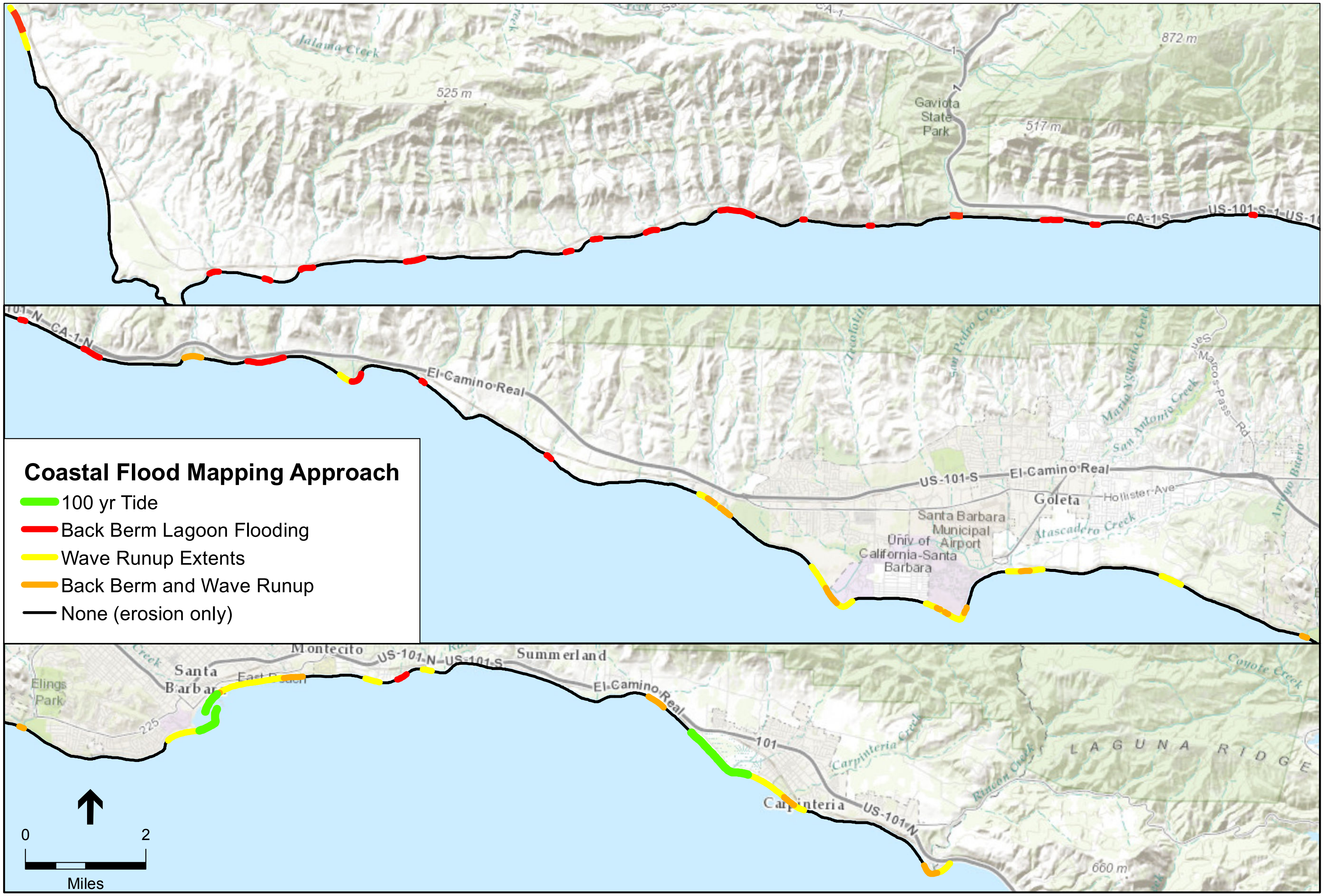


Figure 23
Flood hazard mapping approach by analysis block

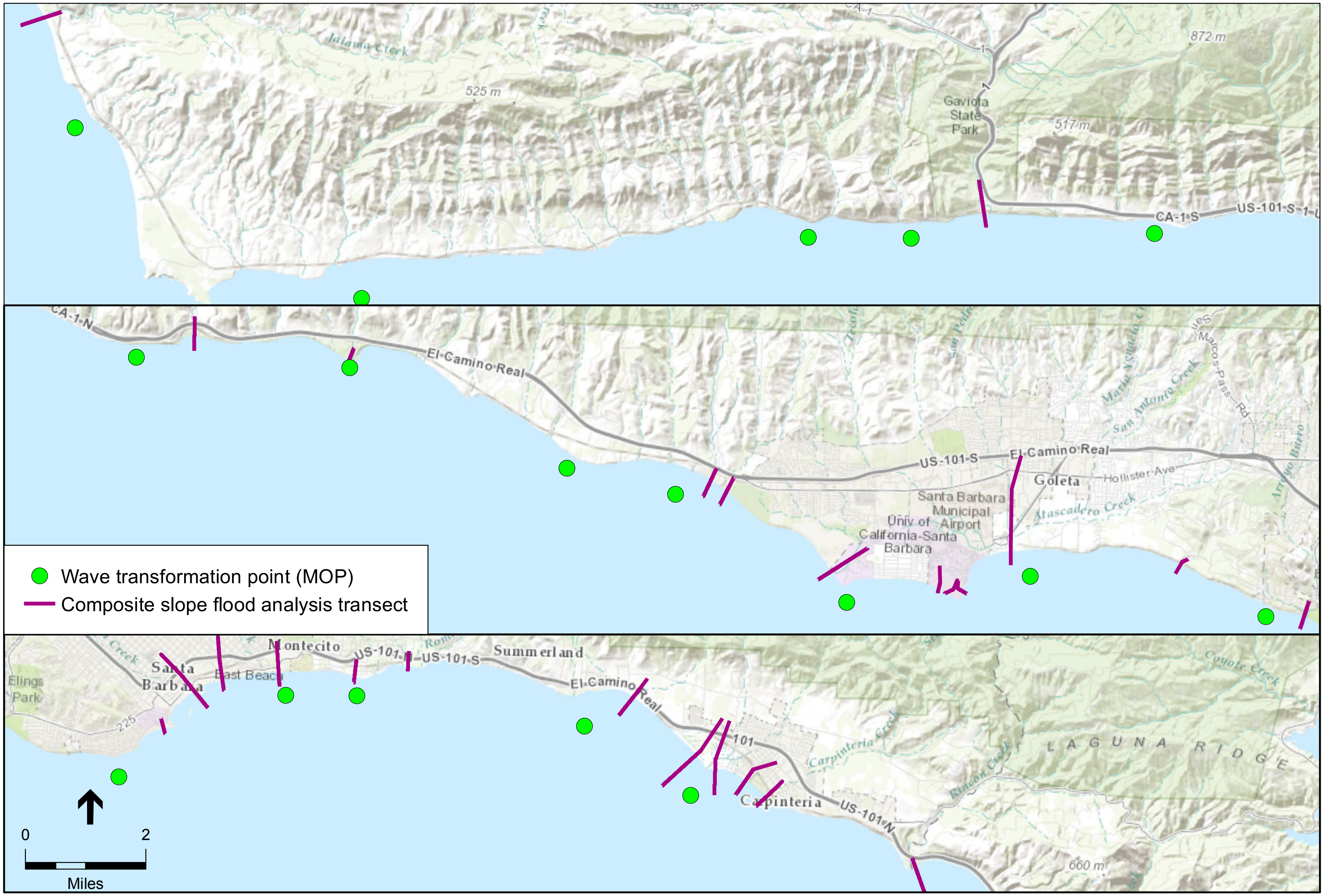
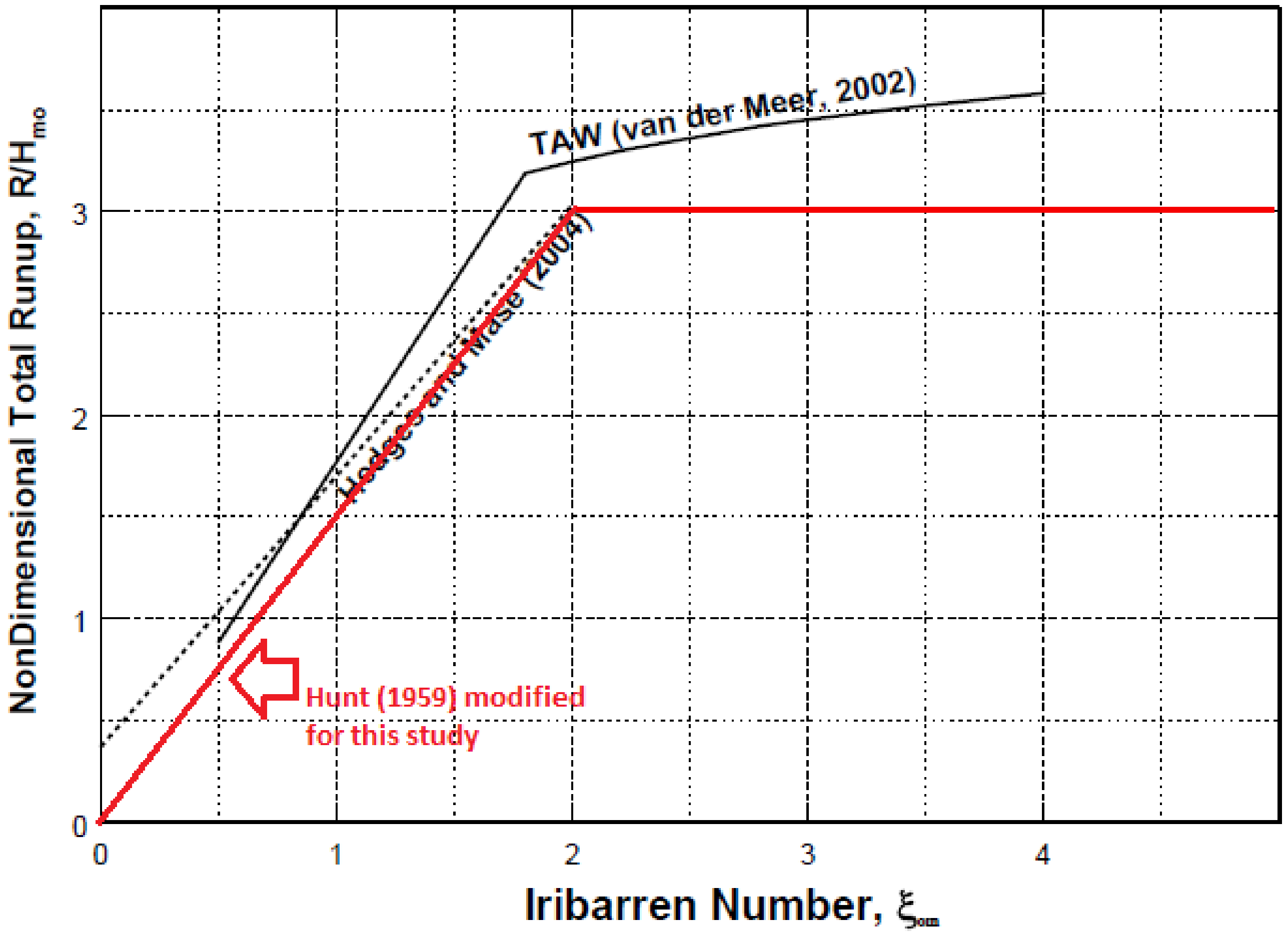


Figure 24

Composite slope profile locations

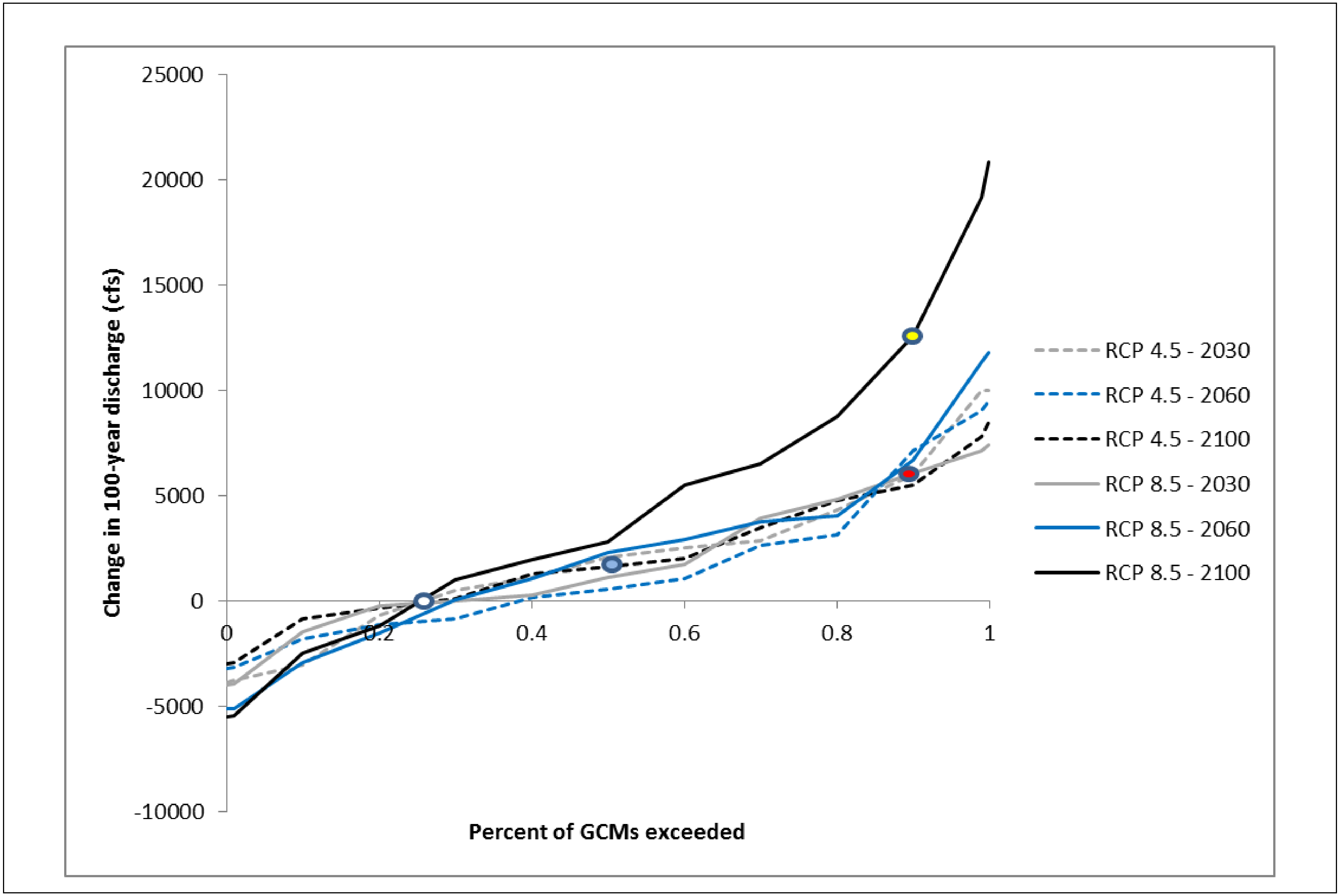


Wave run-up relative to wave height is modeled as being proportional to the Iribarren Number, also known as the Surf Similarity Parameter, which is the ratio of the beach slope to the square root of wave steepness (relative slope steepness). Note that the wave run-up is limited above a value of three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

SOURCE: FEMA 2005a

Figure 25

Non-dimensional total runup vs. Iribarren Number



Points represent selected discharges (white = existing conditions and low SLR scenario at all years; blue = medium SLR scenario at all years; red = high SLR scenario at 2030 and 2060; yellow = high SLR scenario at 2100).

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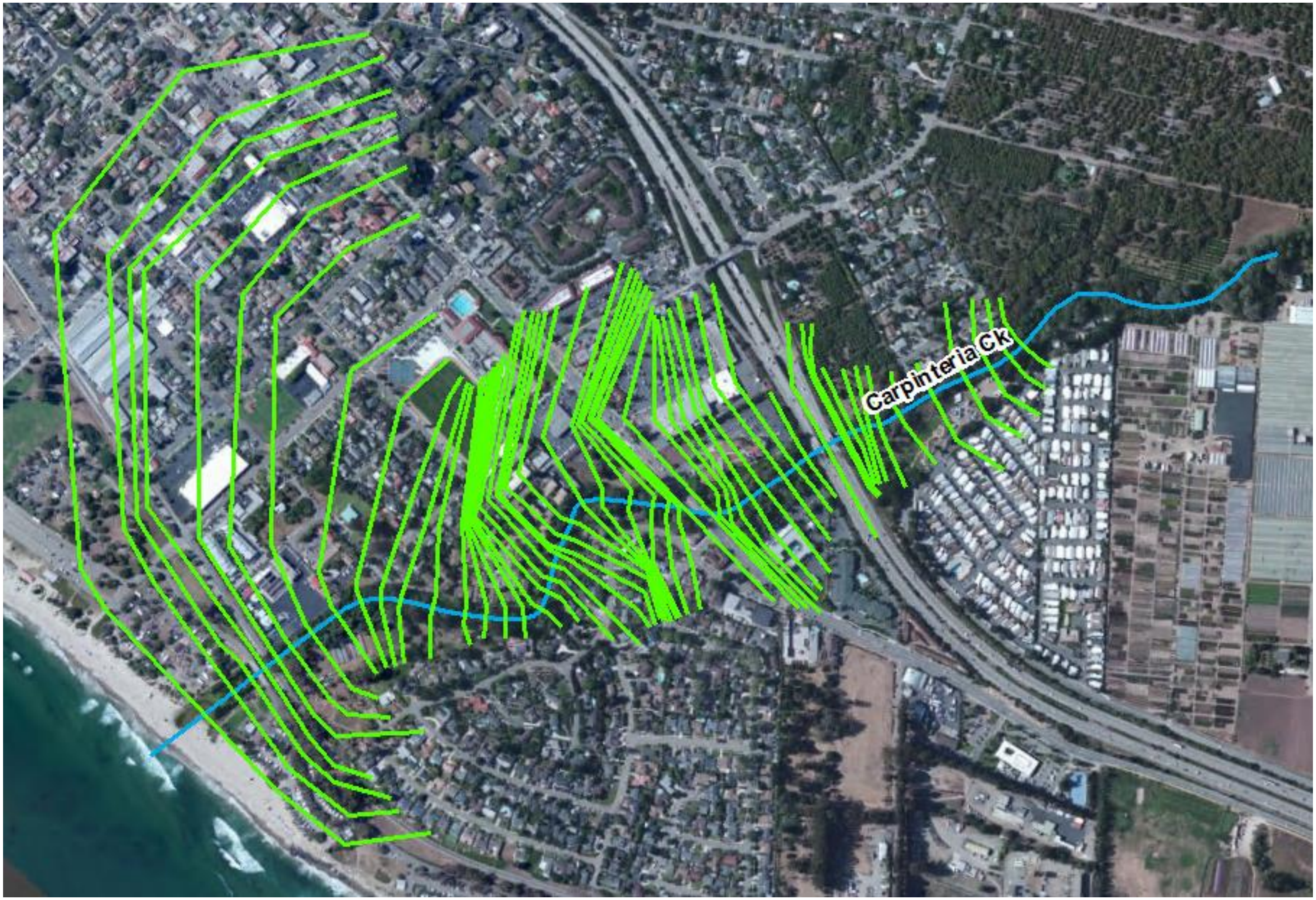
Figure 26

Downscaled climate projections of 100-yr streamflow change on Carpinteria Creek



SOURCE: Avila & Associates, 2014; ESA 2015.

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Figure 27
Carpinteria Creek HEC-RAS model extents