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A methodology for predicting future coastal hazards due to sea-level rise on the California Coast

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Abstract Sea-level rise will increase the risks associated with coastal hazards of flooding and erosion. Along the active tectonic margin of California, the diversity in coastal morphology complicates the evaluation of future coastal hazards. In this study, we estimate future coastal hazards based on two scenarios generated from a downscaled regional global climate model. We apply new methodologies using statewide data sets to evaluate potential erosion hazards. The erosion method relates shoreline change rates to coastal geology then applies changes in total water levels in exceedance of the toe elevation to predict future erosion hazards. Results predict 214 km^2 of land eroded by 2100 under a 1.4 m sea level rise scenario. Average erosion distances range from 170 m along dune backed shorelines, to a maximum of 600 m. For cliff backed shorelines, potential erosion is projected to average 33 m, with a maximum potential erosion distance of up to 400 m. Erosion along the seacliff backed shorelines was highest in the geologic units of Cretaceous marine (K) and Franciscan complex (KJf). 100-year future flood elevations were estimated using two different methods, a base flood elevation approach extrapolated from existing FEMA flood maps, and a total water level approach based on calculations of astronomical tides and wave run-up. Comparison between the flooding methods shows an average difference of about 1.2 m with the total water level method being routinely lower with wider variability alongshore. While the level of risk (actual amount of future hazards) may vary from projected, this methodology provides coastal managers with a planning tool and actionable information to guide adaptation strategies.

1 Introduction

Climate change will affect many aspects of society including water supply, flooding, recreation, and ecosystem services. Accelerated sea level rise (SLR) associated with global

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warming has been identified as a major concern (IPCC 2007). For increasingly populated coastal communities, accelerated SLR will not only inundate coastal areas, but may also significantly impact patterns of coastal change. Coastal erosion is a complex response to many forcing parameters such as marine processes (water levels, waves, sediment supply and transport, etc.), terrestrial processes (rainfall, runoff, wind, etc.), and other instabilities (seismic, biologic, etc.), as well as geology and antecedent topography (Trenhail 2002; Collins and Sitar 2008). The resulting shoreline recession has the potential to significantly endanger public and private resources. Increased storminess and associated wave heights, documented along the U.S. West Coast north of Central California by Allan and Komar (2006), Graham and Diaz (2001), Ruggiero et al. (2010), and Wingfield and Storlazzi (2007) could also exacerbate the effects of higher sea level.

Prior studies that have examined the effect of SLR on the California coast have been confined largely to the San Francisco Bay (Gleick and Maurer 1990; BCDC 2008; Knowles 2009) with one open coast study in San Diego (San Diego Foundation 2008). These studies have only considered inundation over the static landscape. As increased water levels change the location of wave action, erosion and beach profile adjustment (Bruun 1962) can be expected in areas consisting of unconsolidated or loosely consolidated sediments. Quantifying the impact of SLR beyond simple 'bathtub' inundation models is especially important in California as much of the coast is steep, and more susceptible to erosion than direct inundation. The steep geometry is partly the result of tectonics which have uplifted the coast over geologic time scales, which increases the propensity for wave-induced erosion, resulting in bluff and cliff morphologies (Griggs et al. 2005). In most places, the rate of uplift is much slower than sea level rise but can locally affect the relative rate of SLR (Ryan et al. 2008). As a result, a majority of the coastline is backed by seacliffs or sand dunes (Griggs et al. 2005,), and much of this coastline is actively eroding and experiencing loss of land (Hapke et al. 2006). There are extensive private and public developments close to the edge of cliffs or buried in dunes along much of the California Coast. These properties are susceptible to erosion damages but are above the present-day 100-year flood elevation (e.g., FEMA flood maps). Inundation-only modeling approaches show little increase in coastal hazards along higher elevation cliff and dune backed shorelines. For this reason, the California Coastal Commission requires new development to be setback from the shore for a distance based on historic erosion rates and development life expectancy. Historic change rates can be expected to accelerate in the future with SLR, estimates of increased erosion are critical to coastal zone management. This work was funded by the State of California to develop a first-order estimate of the potential erosion and flood hazards resulting from SLR. This work was done in cooperation with the Pacific Institute, Scripps Institution of Oceanography, and the state-federal Coastal Data Information Program (CDIP), with overall project management by the California Ocean Protection Council.

1.1 Previous studies

Previous approaches for evaluating the effects of SLR on coastal change have focused primarily on dune and coastal barrier erosion (Bruun 1962; Dean and Maurmeyer 1983; Leatherman 1984; Kriebel and Dean 1985). Two approaches for assessing dune erosion include an equilibrium profile approach (Bruun 1962; Komar et al. 1999) and a wave impact approach (Larson et al. 2004).

The equilibrium profile approach assumes that over long time scales, an equilibrium profile shape migrates geometrically upward and inland in response to enhanced water elevations whether from SLR or a storm event (Bruun 1962; Komar et al. 1999). The Bruun approach, which has been widely applied to SLR assessments as well as criticized (Pilkey et al. 1993), is less applicable to California due to its diversity of coastal morphologies (cliffs, landslides) and tectonic controls. The wave impact approach accounts for the erosion contribution from individual waves (Fisher and Overton 1984; Nishi and Kraus 1996; Larson et al. 2004); however, this method has not been applied to the assessment of SLR impacts.

In general, the variables controlling cliff erosion can be divided into marine and terrestrial processes (or intrinsic and extrinsic) (Emery and Kuhn 1982; Sunamura 1992; Benumof and Griggs 1999; Benumof et al. 2000; Hampton and Griggs 2004; Young et al. 2009). Given the lack of information at the statewide study scale on the terrestrial processes we assume that historic erosion rates integrate both terrestrial and marine processes, and we drive cliff erosion based on an escalation of marine processes (Robinson 1977; Carter and Guy 1988). The primary marine processes include water levels, wave height, period, and direction, with additional factors including sediment supply and beach sand levels. Several previous studies have found an increase in coastal cliff erosion related to an increase in wave attack and lower sand elevations (Carter and Guy 1988; Komar and Shih 1993; Benumof et al. 2000; Ruggiero et al. 2001; Sallenger et al. 2002; Collins and Sitar 2008). However, it has been noted throughout the literature that cliff geology and rock hardness play an important role in determining erosion rates (Edil and Vallejo 1980; Benumof and Griggs 1999; Budetta et al. 2000). Cliffs composed of hard rock erode slowly and the erosion rate is controlled by material strength and rock mechanics rather than by marine processes. An assessment by the National Research Council (1987) suggested that rising sea level would have a negligible effect on the retreat rate of California seacliffs. Given the diversity of geologic units, wave exposures, shoreline orientations, and sandy beaches fronting the seacliffs along the California coast, this generalization is likely incorrect.

Two USGS National Assessments of Shoreline Change Projects systematically evaluated historic shoreline positions and cliff edges along California to determine shoreline change trends of sandy shorelines and cliff erosion (Hapke et al. 2006; Hapke and Reid 2007). These statewide studies documented trends in coastal change, as well as relationships between shoreline change and cliff recession for certain cliff types. The highest correlations were found along segments of coast predominately affected by marine processes (Hapke et al. 2009).

1.2 Current study

This study aims to assess potential coastal flood and erosion hazards along much of the California coastline for two different SLR scenarios: 1.4 and 1.0 m of rise by 2100 using the methodology of Rahmstorf (2007) as produced in Cayan et al. (2009). To make these results most useful to the planning community and the State government, we predicted future coastal hazard zones at three planning horizons: future years 2025, 2050, and 2100. This study is the first attempt at systematic statewide predictions of future coastal hazards along California and was part of a larger study evaluating the state's vulnerability to sea level rise (Heberger et al. 2009). This larger study was one in a series of studies funded by the California Energy Commission (CEC) that relied on the same global climate model scenario data downscaled for California (Cayan et al. 2009).

1.3 Study area

The California coastline contains a diverse range of geomorphology that is primarily shaped by the local geology and vertical tectonic movements. Across the state, a wide range of shoreline orientations and wave exposures combine with temperature and precipitation gradients to affect the rates of weathering and erosion. For the flood component of the study, the 1% annual recurrence coastal flood elevations, called the Base Flood Elevations (BFEs), were estimated for the entire state. The erosion study area stretched approximately 1,450 km (900 miles) from the Oregon/California border in the north to the Santa Barbara Harbor in the south. Along this stretch some notable segments of coast were not analyzed, primarily along the Big Sur (Monterey County), Devils Slide (San Mateo County), and the Lost Coast (Humboldt County), where the coast is largely dominated by terrestrial mass wasting and landslide processes and data availability is limited. These sites were noted by Hapke et al. (2009) to have a negative correlation between shoreline change and cliff erosion rates indicating that marine processes were not the dominant forcing mechanism in these areas. The southern California coastline was also excluded from the analysis for two primary reasons. First, the most likely coastal management response to SLR, given the large population centers, is likely to be a range of soft and hard engineering solutions (e.g. Flick and Ewing 2009), limiting the applicability of this analysis on natural coastal systems. Secondly, another project funded by the CEC focused on sea level rise impacts to erosion hotspots in Southern California (Adams and Inman 2009).

2 Methods

In this study, we estimate future coastal hazards of erosion and flooding based on two scenarios generated from a regional downscaled global climate model.

The addition of wave runup (also known as uprush) to ocean water level is called the Total Water Level (TWL), and is used to define coastal flood elevations (FEMA 2005). Changes in water levels due to both SLR and the incident wave climate increase future TWL elevations attained along the coast. We hypothesize that increases in the amount of time that waves impact various backshore features, (i.e. the toe of a seacliff or sand dune), increase erosion rates. This hypothesis is supported for short time frames (storms and seasons) by correlation between TWL and dune erosion (Ruggiero et al. 2001) and soft bluff erosion (Collins and Sitar 2008); and in terms of wave height and erosion rate for hard bluff erosion (Sunamura 1982). Antecedent conditions resulting from the timing and extent of geologic uplift and sea level rise greatly complicates attempts to calculate rock erosion due to elevated wave action (Trenhail 2002). These prior studies support the hypothesis that increased water levels and or wave exposure will likely increase coastal erosion rates of soft and hard backshores.

We hypothesize that the increased intensity and extent of wave action on the back shore, in terms of TWLs, due to sea level rise will increase erosion of the backshore, and that the potential erosion response at a particular site can be calculated with consideration of the backshore type, the geology, and the historic shoreline change trends which integrate both the marine and terrestrial erosion processes. The erosion response leads to accelerated erosion, a landward migration of the shoreline and an erosion of upland, with potential inundation of new areas (Fig. 1).

Two data sets are needed to apply this methodology: a coastal backshore characterization and a time series of TWL. Development of these data sets and the estimates of 1% annual coastal flood elevations (BFEs) are discussed below.

2.1 Backshore characterization—geology and backshore type

In order to characterize the morphologic diversity found along the California coast, we combined several statewide datasets representing the backshore type (cliff or dune), coastal

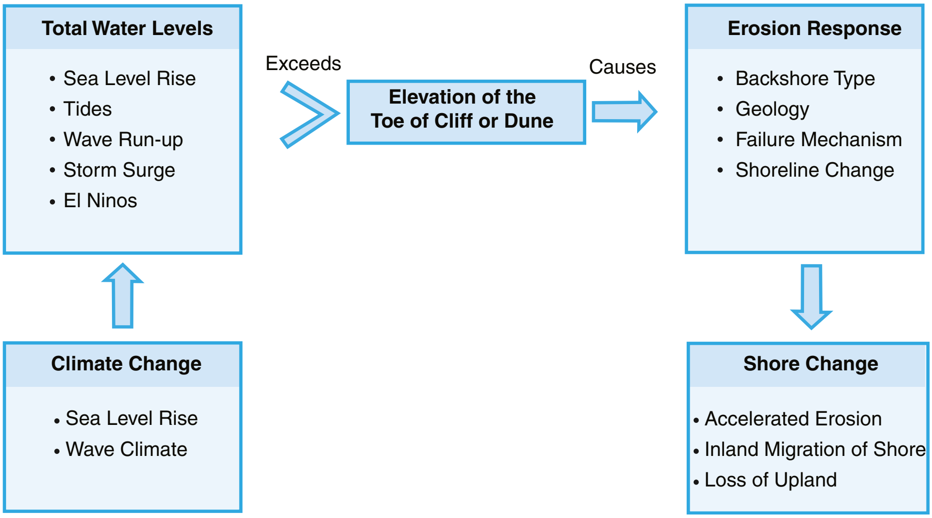

Fig. 1 Conceptual model of coastal response methodology

geology, trends in shoreline change, and various geomorphic features including toe elevations, heights, and beach slopes. These statewide data sets and their source references are described briefly below:

- **Geology**—original data from the California Geological Survey updated by Griggs et al. (2005).
- **Shoreline Inventory—shoreline classification** originally collected by Habel and Armstrong (1978), digitized in 1999, and updated by Griggs et al. (2005).
- **Shoreline Change—**rates from the USGS National Assessment of Shoreline Change in California. These data include: Long term linear regression rates (LRR) for sandy shorelines (1870s to 1998; Hapke et al. 2006), and end point erosion rates (EPR) for cliff backed shorelines (1930s to 1998); along with the 1998 cliff edge delineation used in Hapke and Reid (2007).
- **LIDAR**—shoreline topography collected in April 1998 and October 2002 by NOAA, NASA, and USGS. The primary data set was April 1998, collected to evaluate the storm impacts following the 1997–98 El Niño. The 2002 data set was collected to fill gaps in the 1998 data set and was used where the 1998 data was unavailable.
- **Bathymetry—**10 m contours obtained from California Dept. of Fish and Game. Used to calculate a shoreface beach slope extending from closure depth (estimated at 10 m depth contour) to the toe of the backshore.
- **Foreshore Beach slopes**—Mean high water slopes based on the Stockdon et al. (2002) method. These slopes were used to calculate wave run-up and evaluate erosion from a 100-year storm event.

The data sets above were used to classify the coastline into dune and cliff backed shoreline segments. This classification was applied in GIS to an offshore baseline roughly corresponding with the shoreline inventory of Habel and Armstrong (1978). This backshore baseline was further divided based on geologic units generated during the update of Griggs et al. (2005). Each continuous geologic unit was subdivided into 500 m blocks (Fig. 2). Approximately 2,500 cross shore profiles were extracted from LIDAR topography in

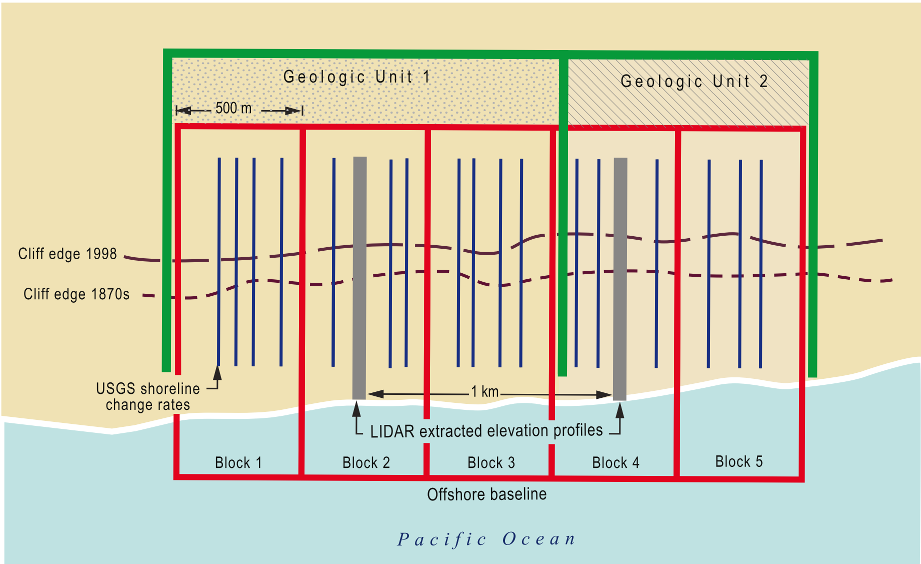

Fig. 2 Method of backshore classification. Backshore classification was based on geologic unit and backshore type. These units were subdivided into 500 m blocks which formed the scale of analysis. For each block, the historic erosion rates from the USGS were averaged and beach slopes and various elevations were attributed to the offshore baseline

ArcGIS©. These profiles were geomorphically interpreted using visual cues to identify significant changes in slope through a custom built interface in MATLAB© to identify toe elevations (Et), foreshore beach slopes, and cliff and dune heights. Attributes necessary to drive the erosion models were averaged over 500 m alongshore segments called blocks and assigned to the backshore baseline. We ground-truthed this data set using a combination of site investigations, oblique air photos from the California Coastal Records Project (www.californiacoastline.org), and topographic information extracted from LIDAR.

Following the initial block averaging only 55% of the blocks had all of the input values necessary to run the erosion models (Table 1). To provide for more complete coverage along the coast, we prioritized the following criteria to fill in missing data gaps for the 500 m spaced blocks:

- Use the block averaged data when available
- Use the geologic unit averaged data continuous with the missing blocks

Table 1 Summary of the backshore characterization comparing USGS published data following application of filtering criteria

	Length (km) (miles)	Total # of blocks	USGS coverage (# of blocks)	USGS% of shore	Current study (# of blocks)	Current% of shore
Cliff	1,142 (710)	3,276	1,607	49.1%	2,897	88.4%
Dune	303 (188)	816	634	77.7%	764	93.6%
Total	1,445 (898)	4,092	2,241	54.8%	3,661*	89.5%

*Blocks with all input parameters necessary to calculate future hazard zones

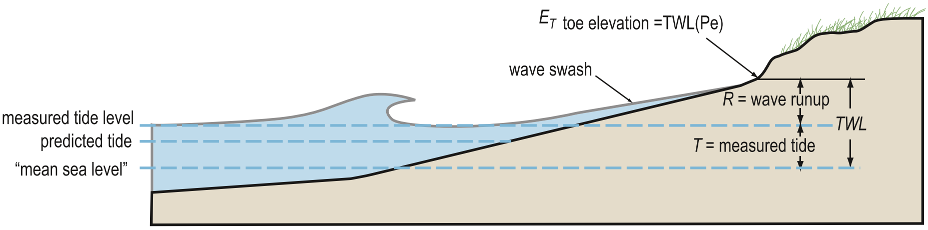

Fig. 3 Total Water Level Definition (after Ruggiero et al. 2001), wave run-up is calculated using the empirical formula of Stockdon et al. 2006

- Use the block averaged LIDAR interpreted profile data
- Use the geologic unit averaged LIDAR interpreted profile data
- Use geologic unit averaged data found in close proximity (+/−15 km)

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

- Remove all toe elevations>6 m
- Elevate all toe elevations<1.0 m up to 1.0 m
- Remove all beach slopes>1:4 (height:length)
- Reduce all long term accretion trends >1.5 m/yr to 1.5 m/yr[1]

2.2 Total water levels (TWL)

The TWL is conceptually the combined elevation of wave effects and ocean water levels affected by tides and meteorology. The TWL is determined by the sum of mean sea level, astronomical tides, and wave run-up, and can be affected by other atmospheric forcing such as storm surge and climatic conditions such as El Niño events (Fig. 3; Ruggiero et al. 1996; Ruggiero et al. 2001). The TWL has been identified as a key parameter in quantifying coastal flood and erosion hazards on the U.S. Pacific Coast (Ruggiero et al. 2001; Sallenger et al. 2002; Hampton and Griggs 2004; FEMA 2005; MacArthur et al. 2006), and has been used to assess the implications of climate change along the U.S. Pacific Northwest coast (Ruggiero 2008).

The SLR scenarios used in the California Climate Impact Assessments were generated from a downscaled global climate model (GCM) analyzed at the Scripps Institution of Oceanography (Cayan et al. 2009). The "high scenario" was a 1.4 m rise by 2100 and a "low" scenario of 1.0 m rise by 2100(Cayan et al. 2009). Tides and wave exposures vary with latitude, so deep-water conditions were characterized regionally in the GCM outputs. The GCM predicted a 100-year time series of 3-hour coincidental still water levels (tides, storm effects, and SLR) at two locations—San Francisco and Crescent City; and waves at three locations—Point Conception, San Francisco, and Crescent City (Cayan et al. 2009). The deep water wave time series from the GCM were transformed through a wave refraction model to 140 nearshore locations along the coast to account for the range

[1] Hapke et al. (2006) also used the best available LIDAR dataset, a 1998 post El Niño survey. Large sediment deposition associated with high rainfall and discharge was identified as a likely cause of highaccretion rates. Realistic value selected after consultation (Hapke Pers.Comm)

of shoreline orientations, wave exposure, and nearshore bathymetry, (O'Reilly et al. 1993; O'Reilly and Guza 1993; O'Reilly unpublished data). The nearshore transformations are part of the CDIP Monitoring and Prediction (MOP) system (CDIP 2008), with this project representing one of its first widespread applications to evaluating coastal hazards.

After receiving the nearshore transformed wave time series, a wave run-up time series was calculated at each 500 m block using the wave run-up equation of Stockdon et al. (2006). Inputs to the wave run-up equation include deepwater wave height, wave period, and foreshore beach slopes. This wave run-up time series was then added to the still water level (SWL) from the GCM to provide a time series of total water level (TWL=SWL+wave run-up) at each site.

Using the TWL time series, the percent time that the TWL exceeded a specific elevation was calculated. This produced a series of exceedance curves (also called cumulative distributions)for each of the individual backshore segments. Figure 4 compares TWL excedance curves under existing (solid line) and future conditions (dashed line) for the range of wave exposures in the erosion study area.

For each of the ~4,100 blocks, a unique set of TWL exceedance curves was calculated at 10-year intervals (2001–2010, 2011–2020, etc.) from the TWL time series. Changes in TWL exceedance frequency were used to force the erosion response models over the various planning horizons. For each block, the frequency of exceedance of the present day toe elevation (Et) and the intensity of exceedance (TWL-Et) were determined. This procedure was repeated for each 10-year interval using two different erosion methodologies for the dune or cliff backshore types.

2.3 Coastal flooding—base flood elevation (BFE)

To evaluate the effects of SLR on coastal flood hazards, we generated two independent estimates of a 100-year flood level. The first estimate focused on updating and expanding the coverage of the 100-year coastal base flood elevations (BFE) originally published by FEMA, while the second estimate was based on calculating a 100-year TWL at each 500 m block.

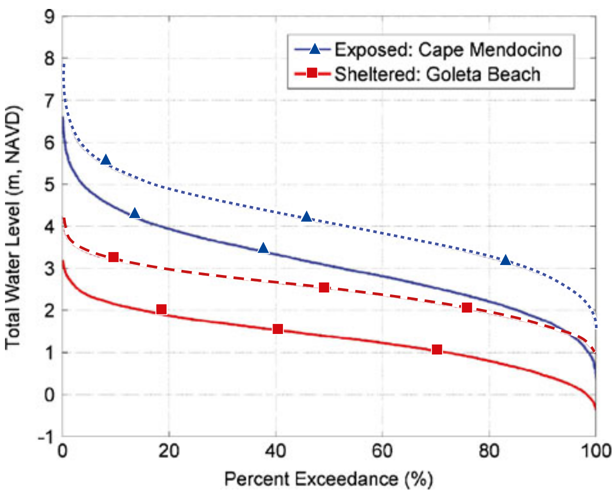

Fig. 4 Example Total Water Level exceedance curves for the most exposed and sheltered coastal segments in the erosion study area. *Solid lines* represent current conditions. *Dashed lines* represent future conditions by 2100

The published FEMA BFEs are an important component in determining flood insurance rates (FIRMs—flood insurance rate maps) and common to land use planning, so this source was chosen to communicate future flood risks. The FEMA BFEs were calculated using methods similar to those used here (based on high ocean water levels coincident with extreme wave runup, see Section 2.2 TWLs), although with less detail consistent with the state of the science in the 1980s when the last studies were done. However, in California, FEMA has not published coastal flood elevations for the majority of the wave-dominated coast, especially along the central and northern portions of the state with low population densities in the 1980s. Sources of published FEMA BFEs included paper maps, FIRMettes, provisional digital FIRMs and effective digital FIRMs. Since the elevations were originally established in the 1980's, elevations were increased by the amount of observed historic sea level rise at the tide gage data for La Jolla, San Francisco and Crescent City gages, representative of southern, central and northern California, respectively. Relative sea level rise was assumed equal to the increase in high tide elevations since the prior tidal epoch (the 19-year period used to calculate tidal datums), which is published by National Ocean Service relative to land datums, and therefore include the effect vertical land motions. We used the most recent tidal epoch 1983–2001, and the prior epoch 1960–1978. A value of 9.1 cm was selected for southern and central California and zero was used for northern California (above Cape Mendocino) since Crescent City showed a relative sea level drop. The elevations were converted to NAVD88 and rounded up to the nearest half foot (15.24 cm) using Corpscon 6.0.1 (ACOE 2005).

The FEMA sources were published at different times and the most recent publication was used for each location. The digital FIRMS are the most recent versions and have been updated from the older National Geodetic Vertical Datum (NGVD) to the contemporary NAVD. Older sources (paper maps) were in NGVD. All published elevations are rounded. The conversion between NGVD and NAVD are not uniform due to different spatial models and data used to develop the datums (hence, the use of Corpscon). Consequently, the combination of different datums, different rounding sequences, and different sea level corrections resulted in site-specific conversions. Each published elevation was assigned to a segment of shoreline within a GIS baseline (different baseline than the coastal backshore characterization).

Where FEMA has not published flood elevations, the flood elevations were estimated using inverse distance weighted interpolation and professional coastal engineering judgment. BFE estimates were informed by the flood elevations published for nearby areas, and consideration of wave exposure. Wave exposure was assessed qualitatively based on the type of land planform (points tend to experience larger waves than embayments due to wave focusing and spreading), shore orientation (the largest wave exposure is from the west to northwest direction), profile steepness (steeper shores have higher run-up elevations), and a general increase with latitude due to the proximity to storms and swells. Small gaps were filled by interpolation unless consideration of wave exposure indicated a different value was appropriate. In some locations, estimates were based on the closest published value with a similar exposure. Results from the BFE methodology were used to evaluate coastal flood impacts (Heberger et al. 2009).

Prior to this study, there was not a single data set of coastal flood elevations in California, and only a few locations had GIS compatible data, and most of the California coast did not have flood maps.

2.4 Coastal backshore response models

2.4.1 Dunes

Dune erosion hazard zones (DHZ) are defined as the coastal band subject to erosion potential over the planning time frame for the sea level rise scenario. DHZ were generated using a location-specific three step methodology (Eq. 1). First, historic erosion rates were multiplied by the planning horizon time step to get the projected baseline erosion. Second, SLR induced shoreline retreat was estimated based on the increased total water level associated with predicted climate change. The third step added a storm-based recession associated with a 100-year storm event occurring at the end of the planning horizon:

$$\mathrm{DHZ} = (\mathrm{R_h})^{*}\Delta t + \Delta \mathrm{TWL}/\tan\varphi + (100 - \mathrm{yr\ TWL})/\tan\beta \tag{1}$$

where

R_h	historic rate of shoreline change
Δt	time step (10 years)
ΔTWL	change in total water level
$\tan\varphi$	shoreface beach slope
$\tan\beta$	foreshore beach slope

Both the shoreline retreat and the 100-year storm event were estimated using the geometric model of dune erosion (Komar et al. 1999; FEMA 2005) but different shore slopes were used. For retreat due to sea level rise, a shoreface slope from MHW to 10 m depth was used. This is similar to the approach by Bruun (1962) and others that the long-term shore recession due to sea level rise relates to the entire zone of wave dissipation (the shore face). In contrast, storm-induced retreat was projected using a foreshore slope (Komar et al. 1999).

Long-term historic shoreline change rates were incorporated to take into account the variety of additional factors such as sediment budget and local geomorphic controls which are not explicitly included in the TWL methodology or resolved in climate modeling. In some cases, the sandy shoreline change rates showed long-term accretion, and in others, localized erosion hotspots. Since the endpoint of the USGS shoreline change study was spring 1998 (following the 1997–98 El Niño), the post El Niño LIDAR data represented an eroded shore. While this eroded condition is consistent with the FEMA guidelines for mapping the 100-year coastal flood (FEMA 2005), the authors consider it less appropriate for the long term changes induced by relative sea level rise. This is because the lower toe elevations indicate a greater TWL exceedance than is normal, as well as other temporary geometries that could affect our baseline from which long term changes are projected. To minimize the influence of the heavy flood and erosion event that occurred just prior to the 1998 LIDAR collection, with its documented impacts of erosion hotspots and large scale beach rotations (Revell et al. 2002; Sallenger et al. 2002; Hapke et al. 2006), we averaged data extracted from the USGS and the LIDAR data sets over each continuous dune stretch and filtered any accretion greater than 1.5 m/yr. We assumed that these localized erosion and accretion signals would be muted as sand dispersed over time along the same stretches of coast that the averaging occurred.

For evaluating the sea level rise impacts, the future toe elevation was established based on the new total water level exceedance curve, assuming the percent exceedance of the TWL above the toe remained constant (Fig. 5a). This was done by moving vertically up from the existing exceedance curve to the future exceedance curve along the present day percent exceedance value (Pe) to intersect at the future toe elevation. This determined the

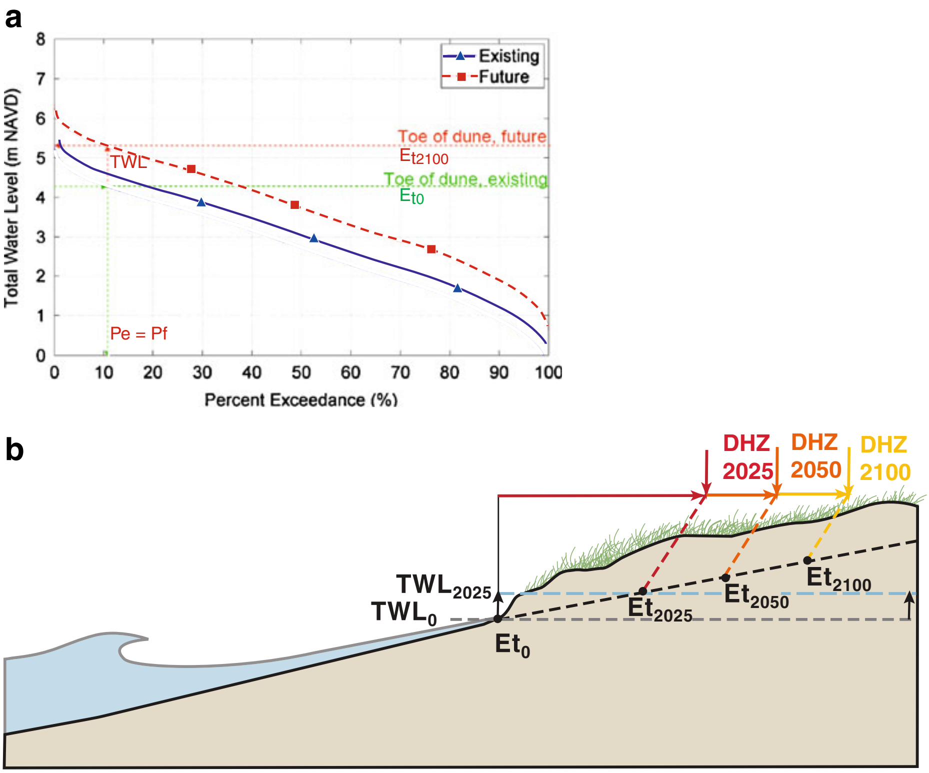

Fig. 5 Dune erosion response model **a** Dune method schematic showing the estimation of future toe elevations and recession from sea level rise **b** Dunes hazard zones in cross section

future elevation of the toe at the specified planning horizon. This future toe elevation was turned into a recession distance by using the average slope of the shoreface calculated from closure depth (estimated as the 10 m contour) to the elevation of the back beach (Bruun 1962; Everts 1985). Finally, the erosion of the toe extended inland through the dune at a

Table 2 Summary of maximum deepwater wave sites and 100-year wave characteristics for each region

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

Ho' is the deepwater wave height; *Tp* is the peak wave period; SWL is the still water level for each MOP site. These results show the most extreme values for each deepwater wave time series. Mendocino (ME), Humboldt (HU), Del Norte (DN); Monterey (MO), Santa Cruz (SC), San Mateo (SM), San Francisco (SF), Marin (MA) Sonoma Counties (SO); Santa Barbara (SB) and San Luis Obispo (SL) Counties standard angle of repose of 32°, the angle of stability for dry sand, to the dune height extracted from the LIDAR transects (Fig. 5b).

The maximum 100-yr TWL was selected for the three regions based on the county groupings shown in Table 2. These values are extreme values from the larger data set of TWL estimates calculated for each block.

The progression of the DHZ with sea level rise is shown schematically in Fig. 5b. A example of the mapped DHZ for the three time projections of 2025, 2050 and 2100 for the high SLR scenario is shown in Fig. 6.

2.4.2 Cliffs

Our methodology for predicting the Cliff Erosion Hazard Zones (CHZ) was to increase (i.e. prorate) the historic cliff erosion rates based on the relative increase in time that the TWL exceeded the elevation of the backshore. This method is an evolution of an erosion prediction method developed by Leatherman (1984), which historic rates of erosion and sea level rise are used to calculate future erosion rates based on predicted SLR. Our method substituted the SLR rate with the change in TWL between planning horizons:

$$R_f = R_h + R_h[(P_f - P_e)/P_e] \quad (2)$$

where

R_f future rate of shoreline change
R_h historic rate of shoreline change
P_f future percent exceedance
P_e existing percent exceedance

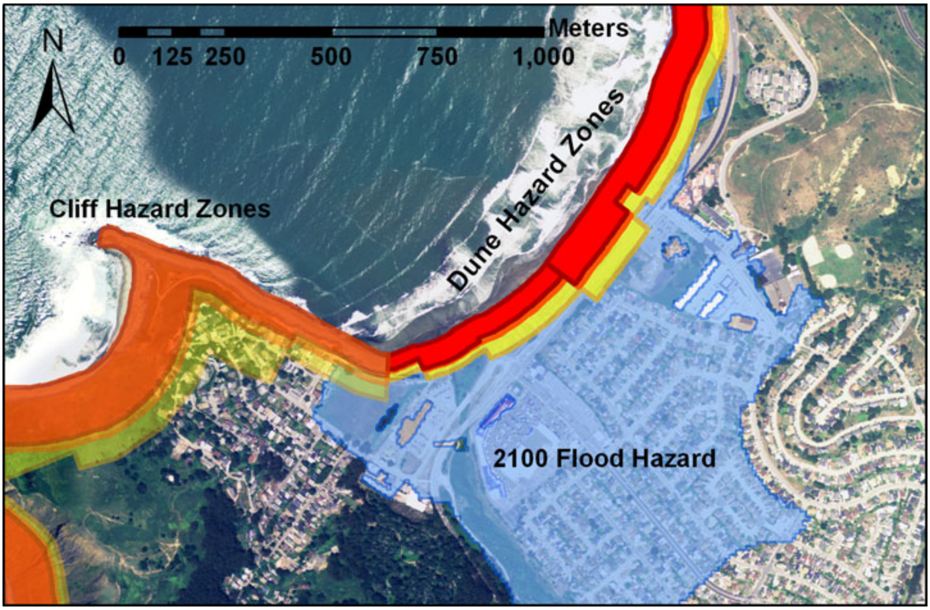

Fig. 6 Example of hazard zones in map view. Cliff hazard zones are on the left, and Dune hazard zones are on the right, with flood hazards extending into the community of Pacifica. Note the steps in the erosion hazard zones demonstrate the differences in alongshore block segment calculations

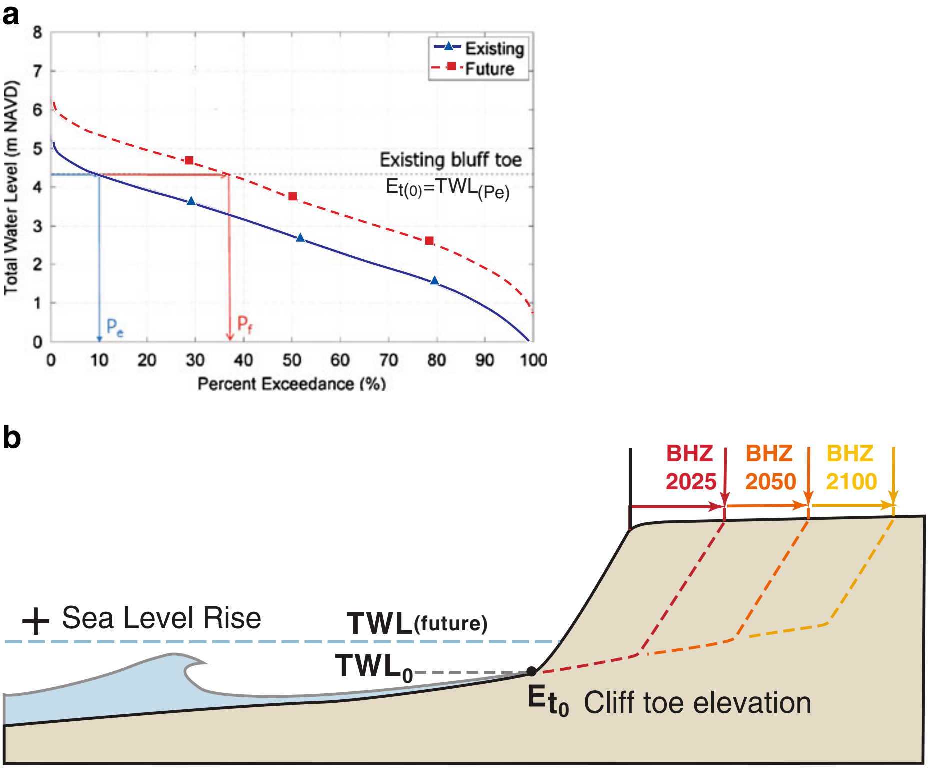

Fig. 7 Cliff erosion response model **a** Cliff method schematic illustrating how changes in percent exceedance are used to prorate the historic erosion rates **b** Cliff hazard zones in cross section

At each 500 m block, we examined Pe and Pf at each planning horizon to determine the change in percent exceedance of the cliff toe (Fig. 7a). This was completed by identifying the present day intersection of the cliff toe elevation (Et) with the exceedance curve. Then moving horizontally, the intersection with the future (next 10 year period) exceedance curve identified the change in percent exceedance assuming a constant toe elevation. This change in percent exceedance was then used to prorate the historic erosion rate at 10 year intervals. For each interval, the prorated erosion rate was turned into a recession distance by multiplying the new prorated erosion rate by the 10 year interval. The overall erosion distance was then the sum of the 10 year recession distances:

$$CHZ = \Delta t^{*}[R_{f\_2020} + R_{f\_2030} + R_{f\_2040} + \ldots] + 2^{*}\Delta t^{*}s_{Rh} \qquad (3)$$

where

Δt time interval (10 years)
R_{f_YYYY} prorated future erosion rate at year *YYYY*
s_{Rh} standard deviation of the geologic unit historic erosion rate

The third term of Eq. 3 was added to account for alongshore variability in erosion rates within geologic units observed in the historic erosion data. We calculated an alongshore variability factor equal to two standard deviations of the historic erosion rates for each geologic unit. This measure of variability was attributed to each block and incorporated into the projected CHZ erosion distances. While this may over-predict erosion in some areas, the landward extent of the CHZ can be conceptualized as a line that connects the most landward erosion "hotspots" even though the precise locations of those hotspots are not predicted. The progression of the CHZ with sea level rise is shown schematically in Fig. 6. An example of the mapped CHZ for the three time projections of 2025, 2050 and 2100 for the high SLR scenario is shown in Fig. 7b.

3 Results

The results are reasonable approximations of the potential extents of coastal hazards that could result under the modeled climate change scenarios. Increased coastal erosion in California in response to SLR and the potential extent of erosion by 2100 indicates severe vulnerability.

3.1 Backshore characterization

The backshore characterization provided some insights into the variability of geomorphic features for shoreline segments found across California (Table 3). The combination of these datasets enabled a prediction of future coastal hazards.

3.2 Coastal flooding—base flood elevations vs. total water levels

The flood potential along the California coast is mapped in a few areas based primarily on analysis accomplished in the 1980s. We have augmented the available mapping in this study using two data sets and related but different methods. Since both methods use Total Water Level (TWL), we have called one method BFE in

Table 3 Summary statistics on backshore geomorphic and shoreline change parameters

Dunes n=816	Min.	Max.	Average	STD.
Toe Elevation, Et (m NAVD)	1.0	5.76	2.17	1.26
Dune Height, Eh (m NAVD)	0	115.74	13.4	15.25
Slope-foreshore (tanβ)	0	0.229	0.08	0.04
Slope-shore face profile (tanϕ)	0.0075	0.0563	0.0174	0.0073
Shoreline change, R_h (m/yr)	−0.76	0.93	0.12	0.33
Cliffs				
n=3,276				
# of geol units=29				
Toe Elevation, Et (m NAVD)	0	6.55	2.32	1.36
Slope-foreshore (tanβ)	0	0.25	0.08	0.056
Erosion Rate, R_h (m/yr)	−2.78	0	−0.28	0.28
Erosion Rate – Geologic Unit Standard Deviation, s_{Rh} (m/yr)	0	0.77	0.18	0.17

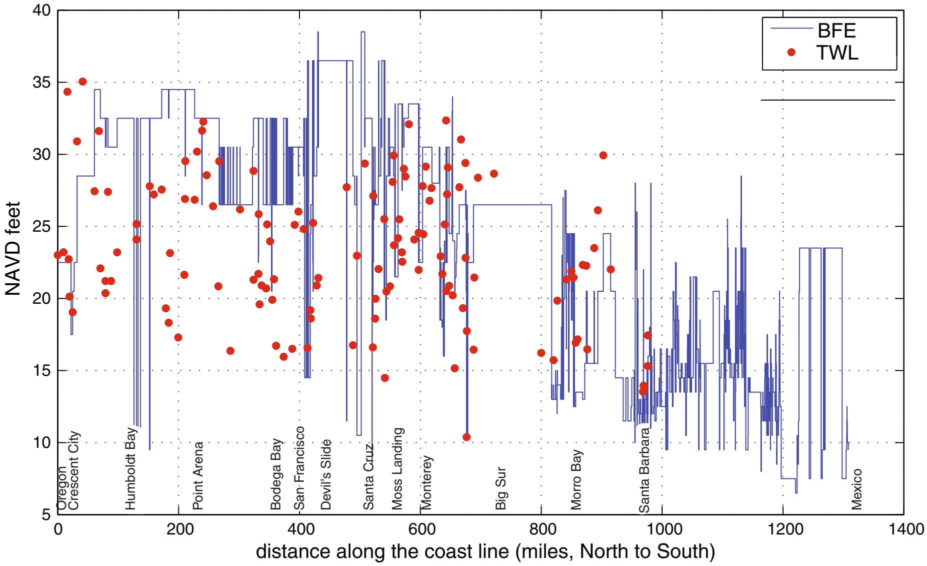

Fig. 8 Comparison of coastal flooding results for the Base Flood Elevation (*lines*) and Total Water level (*dots*) approaches. The TWL approach did not extend into southern California

reference to the FEMA Base Flood Elevation terminology and data source, and use TWL to refer calculations accomplished in this study using GCM water level and wave time series. The calculation of TWL is described in Section 2.2 and the basis for the BFE values is provided in Section 2.3.

The TWL elevations were calculated in this study to force the coastal erosion models and are summarized in Table 2. Figure 8 compares these values to the BFE values. The comparison is an indication of methodology uncertainty because the two sets of estimates entail different data and methods. It should be noted that the BFE is based on FEMA mapping that is accomplished by municipal boundary and calculation points are widely spaced with limited information outside populated areas.

The comparison highlights that flood elevations vary significantly with location. The alongshore variability should be expected since wave heights and wave runup vary substantially along shore due to the variability in bathymetry and topography. Both estimates indicate 100-year flood elevations in northern and central CA mostly between 15 and 35 ft NAVD, which is about 9 to 20 ft above mean higher high water, and lower in southern California.

A direct comparison of the two predictions is undermined by the alongshore variability in values and spacing. However, we estimate that TWL are on average lower than the BFE by about 1.2 m (4 ft). The lower TWL values could indicate that the GCM output is less extreme than historic data in terms of wave conditions and the timing of large wave events with high tides. The lower TWL values may also be more accurate due to the calculation of a 100-year TWL time series rather than less accurate but also less computationally intensive statistical methods used in the 1980's to generate BFEs.

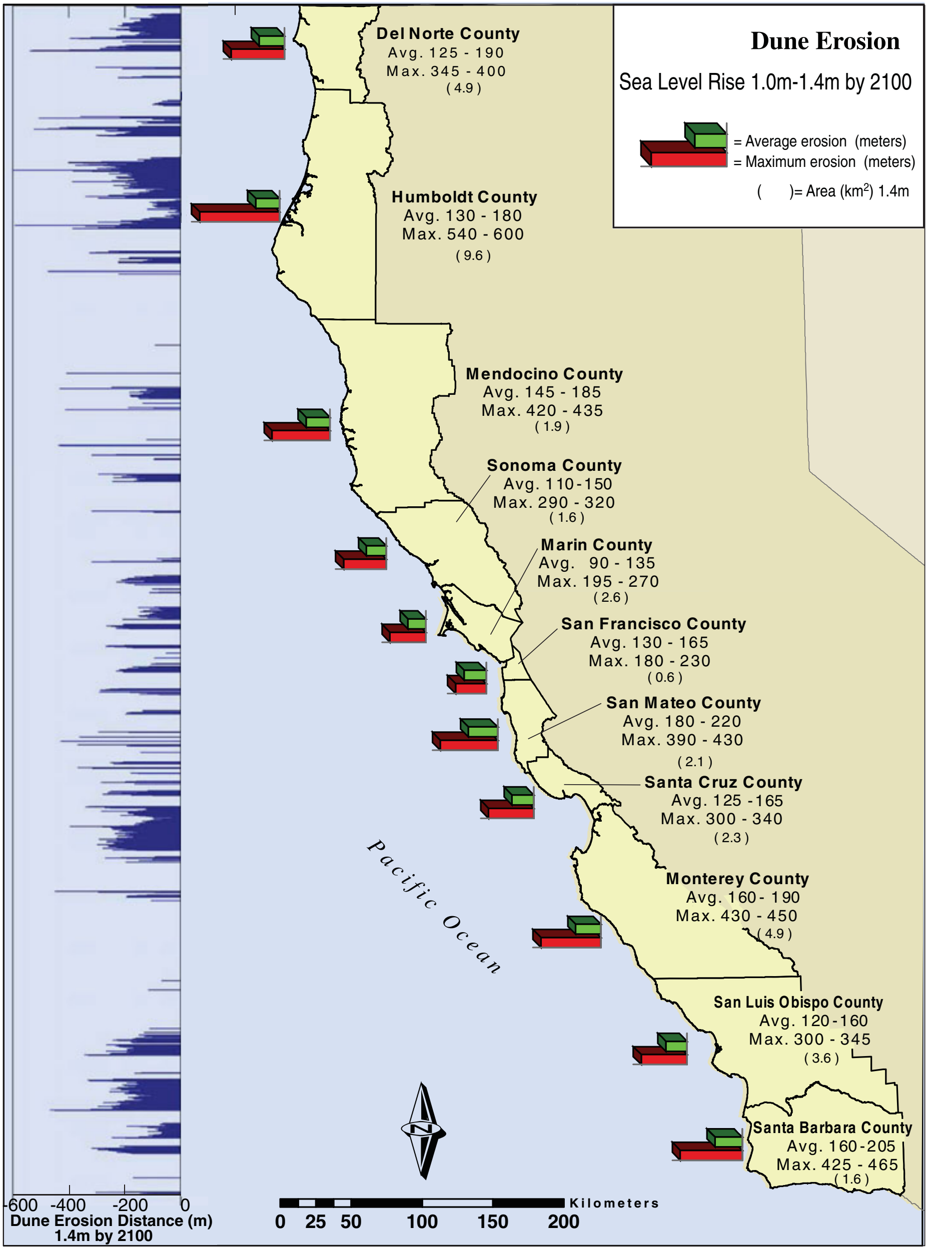

Fig. 9 Summary of erosion hazard results for Dunes by County. Figure shows the range of average and maximum changes for both the 1.0 m and 1.4 m sea level rise scenario. Bar chart on the left of the figure shows the erosion distance calculated at each block for the 1.4 m sea level rise scenario. Predicted erosional area for the 1.4 m scenario is also shown in parentheses

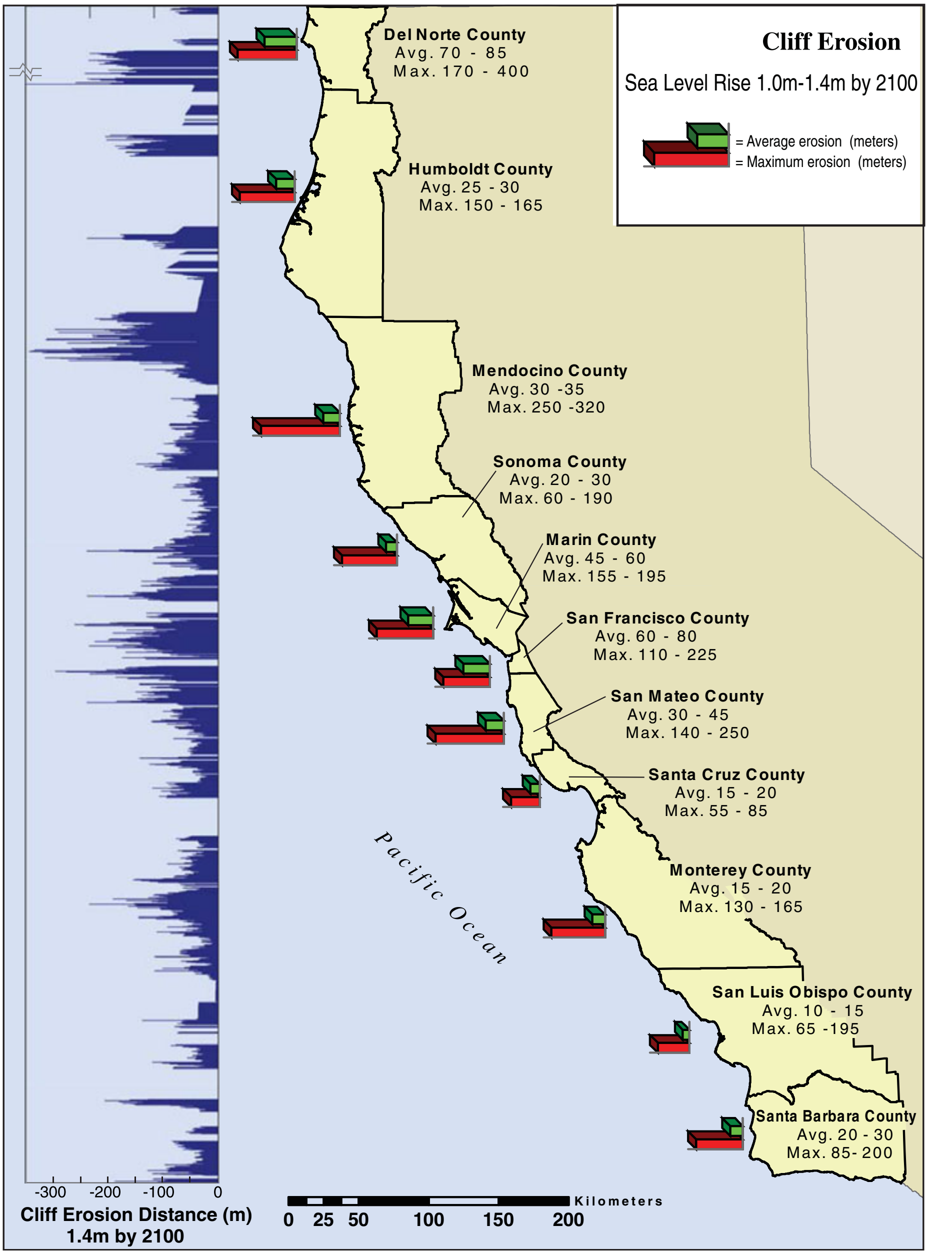

Fig. 10 Summary of erosion hazard results for cliff backed shorelines by county. Figure shows the range of average and maximum changes between the 1.0 m and 1.4 m sea level rise scenario. Bar chart on the left of the figure shows the erosion distance calculated at each block for the 1.4 m sea level rise scenario

3.3 Coastal hazards zones

The erosion hazard zones for both the dunes and cliffs total 214 km^2 within the portions of the 11 coastal counties evaluated in this analysis (Figs. 9 and 10). However, there is significant variation in the areas at risk of erosion. As discussed previously, dunes and cliffs will exhibit different responses to SLR. The potential extent of impacts may be separated from the tabulated time frame, as the timing is less certain than the impact itself. In other words, a given SLR is likely to happen while the time frame for the sea level to reach that particular level is less certain. Also, consider that erosion may lag SLR. The results of the high (1.4 m) scenario analysis for the dune and cliff hazard zones are discussed in detail below.

3.3.1 Dunes

The results for the DHZs at year 2100 are shown in Fig. 9. On average, dunes are projected to erode about 170 m. The dune methodology incorporated three factors, SLR, a 100 year storm event, and historic trends in shoreline change. The relative contribution to the overall average dune erosion hazard zone was 48% for SLR, 45% for a 100 year storm event, and 7% for historic trends. The highest dune hazard zones (>500 m) were found along the northern California coast near Humboldt Bay and nearby lagoon systems, where dunes are projected to erode potentially by as much as 600 m by 2100. In this area, the primary factors contributing to the high hazard predictions were the low lying dunes and ephemeral sandspits located at the entrances to the Mad River and Eel River and various large lagoon systems (e.g., Big Lagoon and Stone Lagoon). Another location of high DHZs occur in Southern Monterey Bay and is related to the high historic erosion rates found along the Fort Ord and Marina shorelines.

The historic shoreline change rates included areas of accretion (Hapke et al. 2006). With these accretion rates projected into the future combined with the effect of SLR subtracted from the accretion, we observe a change in sign from accretion to erosion between 2050 and 2100, when SLR outpaces present day rates of rise and depositional processes.

3.3.2 Cliffs

The results for the CHZs at year 2100 for the high SLR scenario are shown in Fig. 10. On average, cliffs are projected to erode an average distance of about 33 m, based on the prorated erosion. Upon adding in a standard deviation to account for longshore variability in geology average potential erosion across the state could be expected closer to 60 m. Current average percent exceedance of 59% is based on an average toe elevation of 2.59 m NAVD. SLR would escalate this TWL to 69% exceedance by 2100. The 10% proration changes the average cliff erosion rate from −0.31 m/year to −0.42 m/year. In some areas, erosion is projected to be much higher. In Del Norte County, for example, cliffs may potentially erode a maximum distance of 400 m. Cliff erosion is less severe in the other counties along the coast, although remains significant (> 55 m). It should be noted that the historic USGS erosion rates had substantial variation alongshore. A conservative approach incorporated two standard deviations to account for this high variability which greatly escalates potential cliff hazard zones (up to 600 m); however, these conservative results were not reported in the summary result figures (e.g. Fig. 10).

Geologic setting plays an important role in the erosion response of cliff backed shorelines with 29 geologic units identified along the coastline. The geologic units K and Kjf were found to be associated with the highest average cliff erosion rates in California

(−2.8 m/year and −1.8 m/year, respectively). The K unit is a Cretaceous marine unit found predominantly along the northern California coast between Point Arena and Cape Mendocino. This unit is typically a weakly consolidated unit consisting of sandstone, shales and larger conglomerates. The Kjf unit, or Franciscan complex, is found along central and northern California, most notably along some of the landslide backed segments. The Franciscan complex is an accreted terrane (accretionary or tectonic wedge) of heterogeneous rocks. This terrane was scraped off of the Pacific Plate as it subducted under the North American Plate and consists of mafic volcanic rocks including cherts, greywacke, limestones, serpentines and shales all mixed in a relatively chaotic manner. The highest cliff hazards under the high SLR scenario (~400 m by 2100) were located ~3 km south of the Klamath River and are primarily related to the high erosion rates associated with the Franciscan complex.

4 Discussion

The methodology evolved from research along the U.S. West Coast and applied using the best currently available statewide data sets. The results provide an initial assessment of potential future coastal hazards under two possible SLR scenarios. However, uncertainty stems from the limitations of each input data set and the resulting outputs from this study which highlight the need for further research, new data collection, and long term monitoring of geomorphic and physical response variables. Our intent in this discussion is to discuss some of these key findings, identify future work necessary to better predict future erosion, and provide some suggestions on how California and other countries can adapt to climate change.

4.1 Backshore characterization

The backshore was characterized as sandy (dunes) or erosion-resistant cliffs. This classification is not entirely adequate for the complex coastal geology and geomorphology. In some locations, the coastal geology exposed to marine forces changes after some erosion (or accretion) occurs. This is particularly apparent at river mouths with sand spits or dunes fronting cliffs, or in cliffs with multiple geologic units. Some cliffs consist of ancient sand dunes and weakly consolidated sedimentary deposits that can erode as rapidly as sand dunes (e.g. Pacifica; Collins and Sitar 2008). More detailed characterization of the geology and geomorphology (e.g. ranges of toe elevations, rock hardness) would refine the resolution of results. It should also be noted that the geologic units associated with the highest erosion rates (Franciscan complex and Cretaceous marine), are a mix of rock units that are poorly consolidated and often associated with high ground water. Thus, while the erosion models are forced by marine processes, the relation of terrestrial processes with these high erosion rates is important to note. Any new development occurring in these geologic units should require specific study and documentation during permitting to avoid exacerbating groundwater or altering slope stability.

Shoreline armoring was not considered in the erosion analysis. Currently 11% of the California coast is estimated to have shoreline armoring (Griggs et al. 2005) with the majority occurring in southern California. Lack of information on structure heights, condition, and footprint make it nearly impossible to assess the influences of these structures on future conditions at a statewide level. Managers should expect that future use of these structures will come under increasing wave forcing and require higher maintenance costs. Effort to hold the shoreline in place will result in long term losses of beaches, ecology, recreation, and economics. Development of a methodology to specifically address coastal armoring and to allow planning-level evaluation of armored shores should be pursued.

The most comprehensive topographic data available for most of the U.S. West Coast was captured at the end of a major El Niño event in April of 1998. This data set, while spatially comprehensive, represents a single point in time at which the coast was significantly eroded. Data shows areas of eroded conditions characterized by low toe elevations and narrow beaches, as well as other areas which accreted, likely due to sediment deposition following the flood events and erosion of dunes and cliffs. This same LIDAR data was used in the USGS shoreline change studies as the most recent shoreline and likely increased long term erosion rates. The use of this data set for the topographic and geomorphic analysis in this study also likely elevated the prorated erosion rates particularly in the cliff backed shoreline segments due to lower toe elevations. The DHZ calculations may also under-predict the potential erosion hazard. Overall the use of this outdated LIDAR data has introduced unknown levels of uncertainty into this project, but remains the best available statewide data set. This data set is unlikely to represent current conditions at the time of this study. Consequently, recent and routine LIDAR data collection is needed for future analysis. Additional historic shorelines should be incorporated to refine erosion rates.

4.2 Coastal flood elevations

To the authors' knowledge, this is the first time coastal flood estimates have been completed for the entire California coast, and hence it is very difficult to assess their accuracy. The FEMA Pacific Coast Guidelines for Coastal Flood Hazard Analysis and Mapping (FEMA 2005) suggests that one measure of the relative accuracy is to apply multiple methods of prediction that are independent of one another. To that end, the comparison between the TWL and BFE methodologies is insightful, with the TWL method being about 1.2 m (4 ft) lower (Fig. 8). Differences in the TWL method may be due to the use of GCM simulations rather than observed water levels. Additionally, the published BFE values are generally based on studies completed around 20 years ago with sparse resolution and less scientific understanding on wave transformation and run-up modeling. The high variability seen in Fig. 8 compares the two methods and highlights the differing spatial accuracies between the TWL (<500 m) and the BFE (10s of km) estimates.

4.3 Total water levels

The erosion models respond to water level and wave time series output from a downscaled GCM (Cayan et al. 2009). Only GCM output data were used to be consistent with CEC guidance and in order to preserve the implicit coincidence of high water level and waves, and in order to develop an estimate of relative changes. An ensemble of GCM runs could be used to develop a wider range of scenarios with more defined probabilities. More scenarios with different parameters such as changes in wave climate or intensities could also be used to develop a range of erosion and flood responses. For this study only a single wave time series from Crescent City, San Francisco, and Point Conception was used for all scenarios since the GCM did not show any changes to the wave statistics with climate change. However, researchers have shown latitudinal differences in storm wave heights and periods (Graham and Diaz 2001; Allan and Komar 2006; Ruggiero et al. 2010), which was not evident in the GCM output. This would tend to under predict TWLs and hazard zones as one moves north in California. This TWL methodology can account for changes in waves, and their joint probability of occurrence with high water levels, and hence used to explore a wider range of possible climate and management scenarios beyond this present initial application.

While we evaluated over 140 locations along the coast, wave refraction transformations were accomplished only to the 10 m contour. Wave transformations were detailed (using directional spectra), but were condensed to single spectral parameters (wave height and period) for run-up analysis. More detailed wave analysis modules can be used, and may be appropriate for more detailed regional studies.

4.4 Coastal erosion response models

The study purpose was to provide an estimate of ***potential*** future hazards NOT to predict actual erosion or flooding. Actual erosion from SLR may lag potential erosion, especially for very hard shores and/or rapid supply of littoral material. Future erosion was estimated using conceptual models which included simplified geometric response models for sandy dune backed shorelines based on contributions from SLR, a 100 year storm event, and historic trends in shoreline change. For cliff erosion, a prorated linear increase in historic erosion was related to increased TWL exceeding the toe elevation of the cliff.

For dune backed shorelines, we found that over the next 100 years, SLR had the highest relative contribution to the average hazard zone, followed by the 100 year storm event, and finally the historic trends of shoreline change (48%, 45%, and 7% respectively). These relative contributions indicate that the use of historic trends in calculating development setbacks has limited use for future coastal management.

Improvements for the dune backed shorelines could include linkage with a shoreline evolution model and or sediment budget analysis that could allow extension of the profile-based methodology to include planform changes and feedback on wave transformations.

For cliff backed shorelines, the hazard zones are largely affected by the toe elevation and historic erosion rate. At this statewide scale, we used historic erosion as an integrator for the marine and terrestrial erosion processes relying on the spatial relation between geology and erosion rates, as well as the medium time scales to average out the episodic nature of cliff failures for this initial CHZ assessment. Our investigations identified that one of the highest causes for the variability in potential cliff erosion zones was the variability in toe elevations. When low initial TWL exceedance of the toe was a very small percent, erosion rates would rapidly increase to the point of no longer being valid. This could occur if the TWL exceedance increased from just 1 to 10%. These highlight the sensitivity of the model to the input parameters and the need for more detailed site assessments.

In the results we report only the CHZs derived from the proration of historic erosion rates; however given the alongshore variability in geology and failure mechanisms, we recommend adding a factor of safety to these estimates. By adding a standard deviation in geologic unit erosion rates, to attempt to account for alongshore variability, the average potential erosion distance jumped from 33 m to 65 m. In the most extreme cases, this conservative approach identified potential CHZ extending 600 m inland. The expanded ranges from the standard deviations provide a representation of the uncertainties in these projections and should be used if these results are used to make planning and permitting decisions.

Improvements for cliff backed shorelines would include consideration of the duration of wave impact hours as this is likely an important factor not explicitly evaluated in this analysis. Specifically, we did not evaluate failure mechanisms, angles of repose, rock hardness, or terrestrial erosion processes such as rainfall although it has been recently documented that various feedback mechanisms exist between groundwater seepage, elevated TWLs, cliff failures, and toe protection (Young et al. 2009).

The GCM projections of changes to precipitation could have an influence on sediment yield from the coastal watersheds, however the complexities of the water storage infrastructure, varying projections about precipitation patterns, and limited sediment rating curves was beyond the scope of this initial study, but worth future research efforts.

A key improvement of this overall methodology would be to integrate the erosion and flood hazards, time stepping through the erosion calculations and determining any new flow pathways for flooding. This would enhance the estimate of flooding in low lying areas behind barriers, where the volume of overtopping water is often the primary factor in flooding.

During development of this methodology, we identified several alternative erosion response methods based on a range of prior efforts (e.g. Collins and Sitar 2008) and hybrid variations derived from those published (e.g. Leatherman 1984). However, some of the more processed based approaches are not likely to be practical at such a broad spatial scale. A long-term field data collection effort is needed to develop data sets to allow testing of methods, including the ones used in this study. We expect that there is significant room for improvement, and utility in pursuing model validation to improve predictions. While, these results are approximate order of magnitude estimates; we believe that these results provide the magnitude needed in an initial assessment that can be used to guide adaptation strategies to coastal hazards.

4.5 Management implications

Current and future erosion and inundation hazards have lacked systematic quantitative evaluation and remain largely undefined in California, which undermines key coastal zone management tools such as land use plans, local coastal programs and environmental review documents for specific developments. The methodology described herein can be applied at a regional resolution more appropriate for land use planning and coastal management using more site specific information. The methodology allows substitution of methods and values specific to a site, and can therefore be used as a tool to explore scenarios based on a range of assumptions on sediment budgets, climate changes, management regulations, and land uses. However, without higher resolution statewide data sets, further statewide analysis is probably unnecessary. It is recommended that more focused local pilot studies be funded to refine the predictions and methodology.

The potential erosion and flood summary data indicate that a portion of the coast is likely to be lost to erosion over the next 100 years and provide an initial assessment of the spatial impacts to coastal California (e.g. Fig. 6). These impacts will result in the loss of private and public property and threaten or destroy existing public infrastructure such as roads and utilities. Ecological and recreational losses associated with the loss of beaches should also be expected, although the management responses to SLR and accelerated coastal erosion could greatly affect the extent of ecological and recreational losses.

While the exact timing and extents of these coastal hazards are uncertain, the potential erosion mapped during this project is likely to occur at some point in the future. Even if greenhouse gas emissions were to be stopped today, sea levels are expected to rise for thousands of years given the time scales associated with climate processes and feedbacks (IPCC 2007). Adaptation will mean figuring out how to implement land use policies, value hazardous lands, and develop financing mechanisms to relocate infrastructure and development out of these hazardous areas. Management responses to increasing coastal hazards will determine the future economic and ecological value of the coast of California and the world. Attempting to hold the shoreline in place through shoreline armoring will destroy recreation and ecological values of the coast and should be considered carefully as to their long term effectiveness. The spatial representation of coastal hazards is an important step in evaluating levels of risk, developing adaptation strategies, and raising awareness to communities.

5 Conclusions

Sea level rise as a result of climate changes will increase the risks associated with coastal hazards of flooding and erosion. Previous studies of SLR impacts have primarily focused on the inundation of coastal lands; however, along the active tectonic margin of the U.S. West Coast, the variety of coastal morphologies and geologic formations including seacliffs, landslides, and dunes requires a different approach to evaluating future coastal erosion hazards. In this study, we map future potential coastal hazards of erosion and flooding based on two scenarios generated from a downscaled regional global climate model developed to support California impact assessments to climate change. The erosion method relates backshore types (dune and seacliff), with shoreline change rates and coastal geology, then applies future changes in total water levels in exceedance of the toe elevation to predict future coastal erosion hazards for three planning horizons. The results of the erosion study predict 214 km^2 of land loss by 2100 under a 1.4 m SLR scenario. Average potential erosion distances range from 170 m along dune backed shorelines, to 33 m of average erosion for cliff backed shorelines. Maximum potential erosion distances of up to 400 m are predicted along cliff backed and up to 600 m along dune backed shorelines. Erosion along the seacliff backed shorelines was found to be highest in the geologic units of Cretaceous marine (K) and Franciscan complex (KJf). Areas of historic sandy shoreline accretion found along northern California are observed to reverse sign and become erosion between the 2050 and 2100 planning horizon.

In addition, 100-year future flood elevations were estimated for most of the California coast using two different methods. Each method predicts strong alongshore variability. This variability combined with the different location and spacing between calculation points makes a comparison of the two estimates difficult. The more detailed computations using the GCM average about 1.2 m less than the values based on FEMA maps for existing conditions (without SLR).

While the actual amount or time of occurrence of these future coastal hazards may vary from the predicted, the results highlight the need to develop adaptation strategies. This methodology provides coastal managers with a tool that can be applied regionally using higher resolution data sets. By assessing other climate change and management scenarios, coastal managers can develop actionable information to guide adaptation strategies and effectively communicate potential futures to a wide audience.

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