Appendix B

Developing Local Hazard Conditions Based on Regional or Local Sea Level Rise Using Best Available Science

This Appendix provides technical information regarding how to determine local hazard conditions for sea level rise planning efforts. This process is described more broadly as Steps 1-3 in Chapters 5 and 6 in this document, and includes determining a range of sea level rise projections and analyzing the physical effects and possible resource impacts of sea level rise hazards.

Water level varies locally, so this analysis must be performed on a regional or site specific basis, and applicants and planners should prioritize obtaining data or conducting research at the correct geographical scale. The 2018 OPC Sea-Level Rise Guidance is considered the best available science on California's regional sea level rise, and the Commission recommends using it when sea level rise projections are needed. Equivalent resources may be used by local governments and applicants provided that the resource is peer-reviewed, widely accepted within the scientific community, and locally relevant.[97]

Much of the research by the Intergovernmental Panel on Climate Change (IPCC) and others has focused on global and regional changes to mean sea level. However, the coast is formed and changed by local water and land conditions. Local tidal range influences where beaches, wetlands and estuaries will establish; waves and currents are major drivers of shoreline change; and storms and storm waves are often the major factors causing damage to coastal development. It is local conditions that influence beach accretion and erosion, storm damage, bluff retreat, and wetland function.

Local water levels along the coast are affected by local land uplift or subsidence, tides, waves, storm waves, atmospheric forcing, surge, basin-wide oscillations, and tsunamis. Some of these factors, such as tides and waves, are ever-present and result in ever-changing shifts in the local water level. Other drivers, such as storms, tsunamis, or co-seismic uplift or subsidence, are episodic but can have important influences on water level when they occur. The following section discusses these factors in the context of sea level rise and how to incorporate them into planning and project analysis.

In most situations, high water will be the main project or planning concern. For wetlands, the intertidal zone between low and high tides will be of concern, while in some special situations, such as for intake structures, low water might be the main concern. In situations where low water is the concern, current low water is likely to be the low water planning condition and there may be no need to factor future sea level rise into those project or planning situations. In most other situations, hazards analyses will need to account for sea level rise. The following box identifies some of the key situations in which it may be important for coastal managers and applicants to consider sea level rise during project review.

[97] This appendix is written in such a way that it complements the materials from the 2012 NRC Report and the 2018 OPC SLR Guidance, which is currently considered the best available science on sea level rise in California. As new reports are issued in the future, Commission staff will assess whether they should be considered the best available science and update the approaches or terminology in this Appendix accordingly.

General situations needing sea level rise analysis include when the project or planning site is:

- Currently in or adjacent to an identified floodplain
- Currently or has been exposed to flooding or erosion from waves or tides
- Currently in a location protected from flooding by constructed dikes, levees, bulkheads, or other flood-control or protective structures
- On or close to a beach, estuary, lagoon, or wetland
- On a coastal bluff with historic evidence of erosion
- Reliant upon shallow wells for water supply

For situations where future sea level conditions will be important for the analyses of hazards or resource impacts, the following sections are provided as guidance for determining local hazards. Figure B-1 shows the general progression for going from global sea level projections to the possible consequences or impacts that can result from local water levels.

The following information provides guidance on using temporally- and regionally-appropriate sea level rise projections to determine future tidal elevations and inundation, future still water, future shoreline change and erosion, potential flooding, wave impacts and wave runup, and flooding from extreme events[98].

Most of these analyses must occur sequentially. Sea level rise is used to determine changes in tidal conditions, and tidal conditions are combined with future surge, El Niño Southern Oscillation (ENSO) events, and Pacific Decadal Oscillations (PDOs) to estimate local still water. Changes in the frequencies of still water levels will in turn affect erosion rates, and the amount of erosion will affect future wave impacts, runup and flooding.

To be consistent with other sections, these different efforts are presented as Steps, with a discussion of how to accomplish each and the expected outcome. Depending upon the planning or project concerns and required analysis, it may not be necessary to proceed step-by-step and readers should use their judgment as to which items are relevant to their concerns. For example, if the concern is about runup on a non-erosive slope due to an increase in the still water level of 5.5 ft (1.7 m), the guidance on wave runup analysis may be all that is necessary.

[98] Importantly, the 2018 OPC SLR Guidance includes projections tables for 12 tide gauges throughout California, and for every 10 years from 2030 to 2150. As such, adjusting the projections to account for more localized conditions or specific years is likely unnecessary. This is a change from the 2012 NRC report, which included projections for north and south of Cape Mendocino and for only three time periods. Thus, sections within this Appendix that pertained to developing temporally- and spatially-adjusted projections (including mathematic interpolation methods) have largely been removed in the 2018 update.

Step 1 – Develop temporally- and spatially-appropriate sea level rise projections
Step 2 – Determine tidal range and future inundation
Step 3 – Determine still water level changes from surge, El Niño events and PDOs
Step 4 – Estimate beach, bluff, and dune change from erosion
Step 5 – Determine wave, storm wave, wave runup, and flooding conditions
Step 6 – Examine potential flooding from extreme events

A Note on Hydrodynamic Models versus "Bathtub Fill" Models

It is important to be aware of the differences between a so-called "bathtub fill" model and hydrodynamic models, and the related pros and cons of each for analysis of sea level rise impacts. In general, "bathtub fill" refers to those models that analyze flooding or inundation based solely on elevation. In other words, if sea level is projected to rise 3 ft (1 m), thereby increasing flooding/inundation from a current elevation of +10 ft (3 m) to +13 ft (4 m), these models will, in general, flood everything below the +13 ft (4m) elevation. The modeling does not take into consideration whether the new flood areas are connected to the ocean, nor does it consider how the changes to the water level will change wave propagation or overtopping of flood barriers. This is a significant oversimplification of the processes involved in flooding, but it provides value in allowing individuals to gain a broad view of the general areas that could be impacted by sea level rise without requiring a great deal of technical information.

Conversely, hydrodynamic modeling takes into account the details of local development patterns and the characteristics of waves and storms, and can therefore provide a much better understanding of local sea level rise impacts than is possible from "bathtub fill" models. In particular, hydrodynamic models take into account factors that alter flooding and inundation patterns and impacts. Such factors may include the extent and orientation of development – for example, roadways and linear features that tend to channelize water flows, and buildings or flood barriers that can block and divert flows – as well as the conditions that contribute to flooding and inundation, such as wave conditions, flow velocities, the extent of overtopping, and so on. Although the initial development of the modeling grid that is used to depict the community development patterns can be quite time-consuming to create and the model output will change with differing grid designs (Schubert and Sanders 2012), once the grid is developed, hydrodynamic modeling can be used to better characterize areas of flooding and to distinguish areas of concentrated flooding from those areas that may experience small amounts of flooding only during peak conditions (Gallien *et al.* 2011, 2012).

Significantly, many of the analyses described in this Appendix are the kinds of analyses that go beyond "bathtub fill" modeling to include the hydrodynamic factors that help to specify the more location-specific impacts for which planners should prepare.

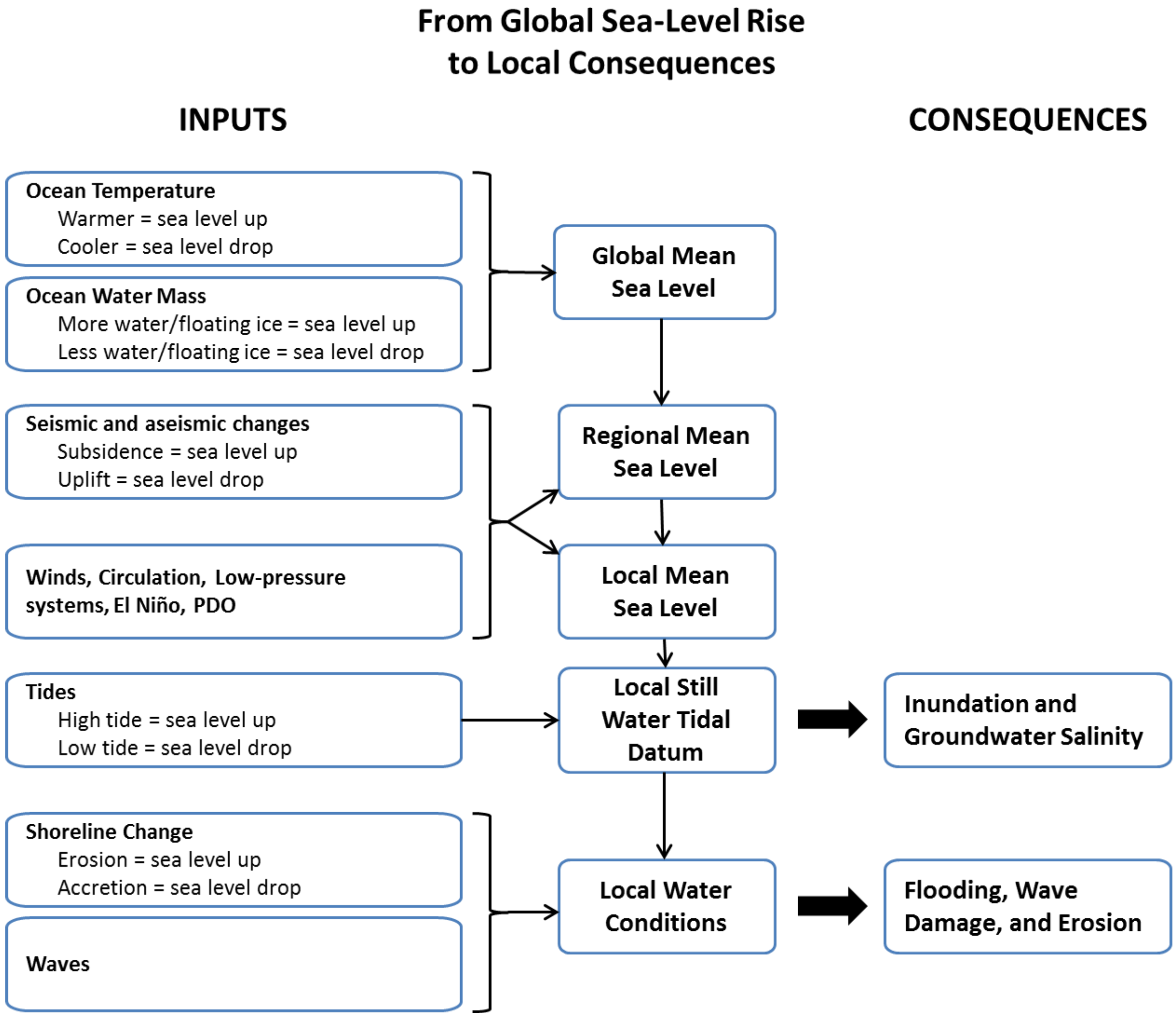

Figure B-1. General process for translating global sea level rise to local consequences

Step 1 – Develop temporally- and spatially-appropriate sea level rise projections

a. Identify the nearest tide gauge

The 2018 OPC Sea-Level Rise Guidance contains projection tables for 12 tide gauges along the California coast in order to account for localized trends in relative sea level rise, related mainly to different rates of vertical land motion. The 12 tide gauges are mapped in Appendix 2 of the OPC Guidance (and copied in Appendix G here). OPC directs users to identify the nearest tide gauge to the project or planning site and to use the associated projection table in planning and permitting. In some cases it may be appropriate to interpolate between two tide gauges (if the project site is equidistant between tide gauges) or to use more locally-specific scientific data, if available. In many cases, though, the differences among projections (either between two tide gauges or from more localized data) are likely to be small, and therefore may be insignificant compared to overall uncertainty in modeling and/or future greenhouse gas emissions scenarios.

b. Determine appropriate planning horizon or expected project life and identify relevant sea level rise projections

The first step in a sea level rise analysis is to determine the appropriate planning horizon based on the expected life of the project. The longer the life of a project or planning horizon, the greater the amount of sea level rise the project or planning area will experience.

Local governments should select their planning horizons to evaluate a broad range of planning concerns. Planning horizons could address the 20-year time period that is typical for *General Plan* updates as well as the long-range planning that is necessary for infrastructure and new development. The 20-year planning horizon may help identify areas within the coastal zone that are now or will soon be vulnerable to sea level rise related hazards as an aid for focusing adaptation planning on the areas of greatest need. Local Coastal Program (LCP) planning will likely use multiple planning horizons and undertake hazards analyses for multiple time periods, multiple sea level rise projections, or both.

At the project level, the LCP may provide insight into the time period that should be considered for the expected project life. At present, LCPs typically provide only a single standard (if any) for the expected life of a structure or development, such as 50, 75, or 100 years. Future LCPs and LCP Amendments (LCPAs) may find it useful to provide greater guidance on expected project life, with differentiations among major development or use classifications. For example, a general range may be chosen based on the type of development such that temporary structures, ancillary development, amenity structures, or moveable or expendable construction should identify a relatively short expected life of 25 years or less. Residential or commercial structures, which will be around longer, should choose a time frame of 75 to 100 years to consider. A longer time frame of 100 years or more should be considered for critical infrastructure like bridges or industrial facilities or for resource protection or enhancement projects that are typically meant to last in perpetuity.

For projects with long lead times, the analysis of impacts from sea level rise should use the projections for the time period when the development will be in use, rather than the current period because the trajectory of future sea level rise is not expected to be linear. For example, a project built today will experience less sea level rise over a 50-year lifetime (about 1.9 feet under the "medium-high risk aversion" scenario at the San Francisco tide gauge) than the same project if it were built in the year 2050 (about 5 feet under the "medium-high risk aversion" scenario at the San Francisco tide gauge). Thus, it is important to understand the anticipated project life of a structure and the associated planning horizon before starting an analysis for sea level rise concerns.

As explained in Chapters 5 and 6, the point of this step is not to specify exactly how long a project will exist (and be permitted for), but rather to identify a project life timeframe that is typical for the type of development in question so that the hazard analyses performed in subsequent steps will adequately consider the impacts that may occur over the entire life of the development.

Once the appropriate planning/project horizon has been identified, the associated projection for that time period can be identified using the projection tables from the 2018 OPC SLR Guidance. These tables include projections for each decade from 2030 to 2150.

As explained elsewhere in this Guidance, project characteristics (including its ability to withstand or adapt to different sea level rise amounts and the consequences associated with underestimating the amount of sea level rise that occurs) should guide users in choosing which scenario to assess for a particular planning horizon. As general guidance, the Coastal Commission continues to recommend that planners or project applicants take a precautionary approach by evaluating higher sea level rise amounts (for example, the medium-high risk aversion scenario for most development, or the extreme risk aversion scenario for critical infrastructure).

Step 2 – Determine tidal range and future inundation

One of the most basic examinations of changing sea level conditions has been to determine the new intersection of mean sea level or other tidal datums[99] with the shoreline. This is a basic "bathtub" analysis since it looks only at the expansion of areas that will be inundated (*i.e.*, regularly submerged under water) or subject to tidal or wave action. For example, future subtidal levels would be the current subtidal limit plus projected regional mean sea level rise. Future intertidal zones would be bounded by the future higher high tide level (current higher high water plus projected regional sea level rise) and future lower low tide levels (current lower low water plus projected regional sea level rise).[100] For some projects, such as wetland restoration, the identification of future inundation zones may be the only sea level analysis needed for project evaluation. However, if the shoreline is eroding, the location of this elevation would need to also incorporate the rate of erosion. So, if the shoreline is expected to erode due to increased wave attack, not only will the intertidal zone move up in elevation, it will be both higher than and inland of the current zone.

Future Water *Elevation* = Current Tidal Datum + Projected Sea Level Rise

OR

Future Water *Location* = Intersection of Future Water Elevation with Future Shore Location

Future water location will extend to the new inundation elevation on the future shoreline. On beaches with a gradual slope, this can move the inundation location significantly inland, based on the geometric conditions of the beach. (This type of analysis is often called the Bruun Rule). On a stable beach with a slope of 1:X (Vertical:Horizontal), every foot of vertical sea level rise will move the inundation area horizontally X feet inland. For a typical 1:60 beach, every foot of sea level would move the inundation zone inland by 60 ft. If the beach is eroding, the loss due to erosion will add to the loss resulting from inundation.

Figure B-2 shows the influence of tides and sea level rise on low-wave energy beaches. Table B-1 provides some useful resources for inundation studies. Local Tidal Elevations are available from tide gauges maintained by NOAA. Where there are no nearby gauges, NOAA recommends the VDatum software.

99 Tidal datums are based on the latest National Tidal Datum Epoch (NTDE) published by NOAA and are the mean of the observed sea levels over a 19-year period. The latest published epoch is 1983-2001. This tidal epoch can be considered equivalent to the year 2000 baseline for the **OPC** projections.

100 Historical trends of high and low tide have changed differently than mean sea level (Flick *et al.* 2003). Based on historical trends, the changes to various tidal elements are likely to track closely with, but not identically with, changes to mean sea level. The future variability of changes to the tidal components, compared with changes to mean sea level will normally fall within the uncertainty for sea level rise projections and can be disregarded in almost all situations. As this phenomenon of tidal change is better understood and can be modeled, it may be appropriate in the future to include the changes in tidal components into the analysis of inundation and various water level projections.

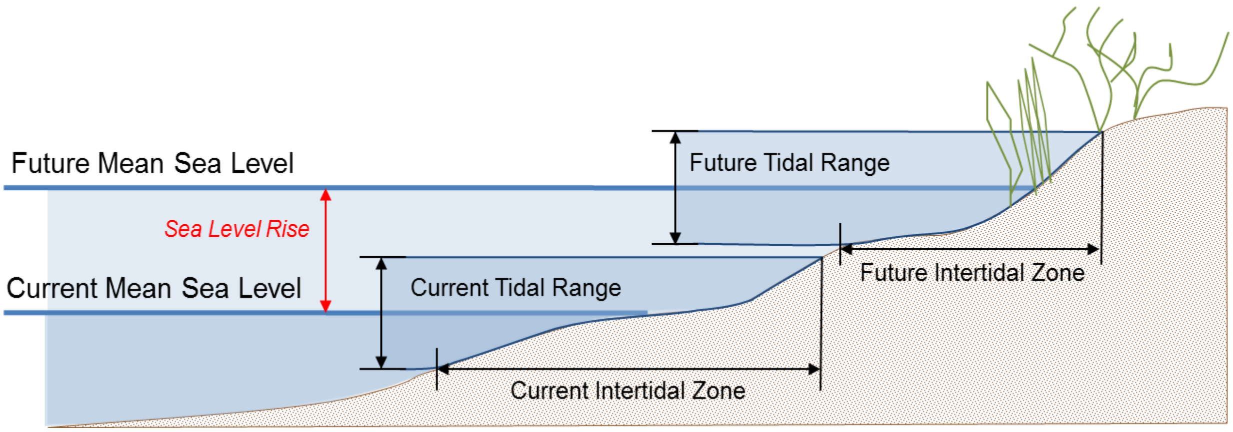

Figure B-2. Sea level rise and changes to tide range and intertidal zone. (*Source: L. Ewing, 2013*).

Table B-1. General Resources for Inundation Studies

Resource	Description	Link
Aerial Photographs	Useful for general information on shoreline trends; ortho-rectified photos can help quantify trends.	California Coastal Records Project, www.californiacoastline.org; Huntington Library; Local Libraries
LIDAR	Fairly detailed topography providing GIS layers for current conditions and comparable with LIDAR data sets for temporal changes.	NOAA Digital Coast, http://coast.noaa.gov/digitalcoast/data/coastallidar
Topographic Maps	Useful for basemaps to overlay site changes; often not at a scale to distinguish small changes in inundation or tidal action.	USGS Map Center, http://www.usgs.gov/pubprod/maps.html
NOAA Sea Level Rise and Coastal Flooding Impacts Viewer	Useful to show changes in water level location if there are no changes in the land due to erosion.	NOAA Digital Coast, https://coast.noaa.gov/digitalcoast/tools/slr.html
NOAA Tidal Data	Measured and predicted tidal components for locations along the open coast and in bays.	NOAA Center for Operational Oceanographic Products and Services, http://tidesandcurrents.noaa.gov/
NOAA Technical Report NOS 2010-01: *Technical Considerations for use of Geospatial Data in Sea Level Change Mapping and Assessment*	Provides technical guidance to agencies, practitioners, and decision makers seeking to use geospatial data to assist with sea level change assessments.	NOAA National Ocean Service http://www.tidesandcurrents.noaa.gov/publications/tech_rpt_57.pdf

VDatum Software	A Vertical Datum Transformation program that allows users to transform geospatial data among various geoidal, ellipsoidal and tidal vertical datums.	NOAA National Ocean Service, https://vdatum.noaa.gov/
Cal-Adapt – Exploring California's Climate	Represents inundation location and depth for the San Francisco Bay, the Sacramento-San Joaquin River Delta and California coast resulting from different increments of sea level rise coupled with extreme storm events. Incorporates real, time series water level data from past (near 100 year) storm events to capture the dynamic effect of storm surges in modeling inundation using a three dimensional hydrodynamic model (per Radke et al., 2017).	http://cal-adapt.org/tools/slr-calflod-3d/
Estimating Sea Level for Project Initiation Documents	Provides guidance on converting tidal datums and predicting future sea levels.	Caltrans Office of Land Surveys, http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/Estimating_Sea_Level_v1.pdf

Outcome from Step 2: *Provide information on the projected changes to the tidal range and future zones of inundation. For locations without any influence from erosion, storm surge, or wave energy, the identification of new inundation areas may be sufficient for project analysis and planning efforts. This projected new inundation area may also be useful for anticipating the likely migration of wetlands and low-energy water areas or as input for analysis of changes to groundwater salinity. For most open coast situations, this information will be used to inform further project planning and analysis that examines erosion, surge and storm wave conditions.*

Step 3 – Determine still water changes from surge, El Niño events, and PDOs

Estimates of surge, El Niño, and PDO water elevation changes are developed primarily from historical records. There are no state-wide resources for this information, although it may be included in some Regional Sediment Management Plan studies. General guidance on water level changes that can be expected from surge, El Niño events, and PDOs is provided in Table B-2.

The remaining discussion provides general information on some of these phenomena. It is provided to acquaint readers to the main issues associated with each phenomenon. Readers with a strong background in ocean-atmospheric conditions may want to skim or skip the rest of this section.

The Pacific Ocean is a complex system. Sea level in the Pacific Ocean responds to multiple oceanic and atmospheric forcing phenomena, occurring with different intensities and at different temporal and spatial scales. Some phenomena may reinforce each other, while others may act in opposition, reducing the net effect. Scientists and researchers are attempting to identify the various signals from the multiple phenomena, but these are nascent sciences and there is still much we need to learn.

Regional water levels can be influenced by surge as well as by high and low pressure systems. Surge is a short-term change in water elevation due to high wind, low atmospheric pressure, or both. It is most often associated with East Coast and Gulf Coast hurricanes that can cause up to 15 or 20 ft (4-6 m) or more of short-term water level rise over many miles of the coast. Along the West Coast, storm surge tends to be much smaller, and is rarely a coastal hazard, except in enclosed bays. In southern California, it rarely exceeds 1 ft (0.3 m) and in central California, it rarely exceeds 2 ft (0.6 m). Surge becomes a concern as one of several cumulative factors that cause a temporary rise in sea level. Each rise may be small, but when surge occurs during high tides and/or in combination with storms, it increases the threat of coastal flooding, wave impacts, and erosion.

Two of the more recognized phenomena that affect water temperature in the Pacific are the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). ENSO cycles, which occur on inter-annual timescales (approximately 2-7 years), not only involve ocean-basin-spanning changes in sea surface temperature (SST) and in the depth of the mixed layer in the Equatorial Pacific, but also drive changes in ocean conditions and atmospheric circulation at higher latitudes. El Niño events result in the transfer of warm surface waters into the normally cool eastern equatorial Pacific, resulting in elevated SST and water levels along much of the west coast of the Americas. El Niños also tend to increase the strength and frequency of winter low pressure systems in the North Pacific. These events can persist for months or years at a time, and strongly influence local and regional sea level. For example, the pulse of warm water from the large 1982-83 El Niño caused water levels along California to be elevated by approximately 0.4-0.7 ft (0.12-0.21 m) for many months, with short-term water elevation peaks up to approximately 1 ft (0.3 m; Flick 1998). The opposite phase of ENSO, characterized by unusually cool SSTs and lower water elevations along the eastern Pacific margin, are called La Niña events. Between El Niños and La Niñas are periods of neutral SST and water elevation changes.

The PDO is an ENSO-like pattern of SST and atmospheric variability occurring over multiple decades. In contrast to ENSO, the PDO is more strongly expressed in the North Pacific than in the tropics. The positive or warm phase of the PDO is associated with unusually warm surface water throughout the eastern North Pacific (along the western US coast), while the negative or cool phase PDO is associated with colder than normal waters. As with the ENSO effects, the warm phase PDO has tended to cause elevated sea levels in the eastern Pacific and along the California coast, while the cool phase of the PDO tends to lower sea level in this region.

The PDO has basin-wide influence. Elevated water levels in one part of the Pacific are often accompanied by lowered water levels elsewhere. The cool phase PDO can result in a drop of water level along the eastern Pacific (western US Coast) and a rise in water level along the western Pacific. Recently, sea level along the western Pacific has been rising about three times

faster than the global mean sea level rise rate, due in part to the PDO (Bromirski *et al.* 2011; Merrifield 2011). This does not mean the eastern Pacific will experience sea level rise that is three times faster than the global mean sea level rise when there is the next shift in the PDO, but does show that the PDO can have a major influence on basin-wide and regional sea level.
The above discussion of El Niño and the PDO may suggest that they are well-understood phenomena, with easily anticipated changes in sea level. However, it is important to note that El Niños have varying strengths and intensities, resulting in different sea changes from one event to the next. Also, changes in regional mean sea level along the eastern Pacific have not always shown a strong connection to the PDO cycles. An apparent jump in regional mean sea level occurred after the mid-1970s shift to the warm phase of the PDO, yet the expected continued rise in sea level along the West Coast seems to have been suppressed by other forces. Tide gauge records for the Washington, Oregon, and California coasts have shown no significant inter-annual rise in sea level from 1983 to 2011 (Cayan *et al.* 2008; Bromirski *et al.* 2011; NOAA 2013). Bromirski *et al.* (2011, 2012) postulate that persistent alongshore winds have caused an extended period of offshore upwelling that has both drawn coastal waters offshore and replaced warm surface waters with cooler deep ocean water. Both of these factors could have caused a drop in sea level, canceling out the sea rise that would otherwise be expected from a warm phase PDO signal.

Water level changes from surge, atmospheric forcing, El Niño events and the PDO can occur in combination. The water elevation changes from each factor may be only about 1 ft (0.3 m) or less, but each can cause changes in the water level over a time period of days, months, or a few years – far more rapidly than sea level rise. In combination, they can potentially cause a significant localized increase in water level.

When high water conditions occur in combination with high tides, and with coastal storms, the threat of coastal flooding, wave impacts and erosion also increases. These conditions can be additive, as shown in Figure B-3. Also, these changes in water level will continue to be important to the overall water level conditions along the California coast and they need to be examined in conjunction with possible changes due to regional sea level rise.

As stated earlier, estimates of surge, El Niño and PDO water elevation changes are developed primarily from historical records. There are no state-wide resources for this information, although it may be included in one of the Regional Sediment Management Plans, available for many coastal areas (see http://www.dbw.ca.gov/csmw/). General guidance on water level changes, surge, and El Niño events is provided in Table B-2.

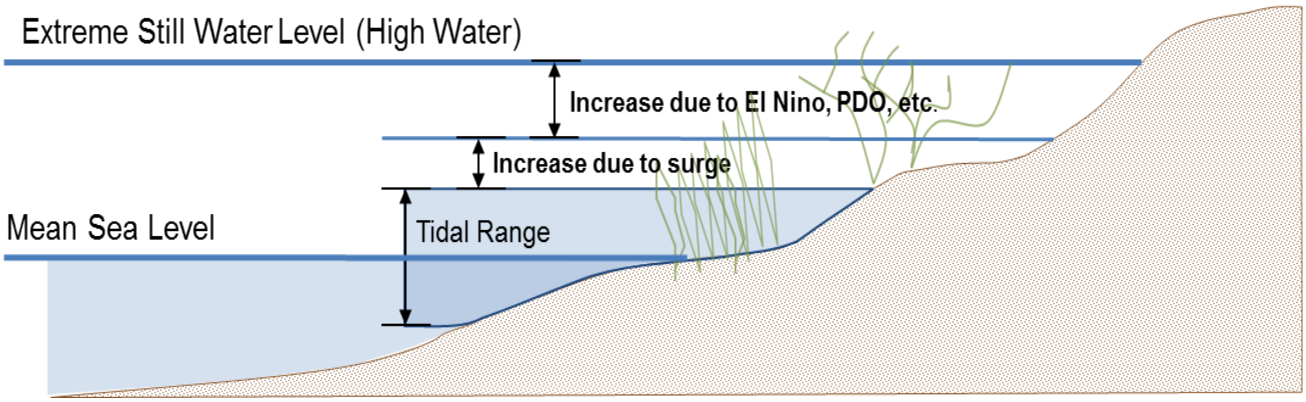

Figure B-3. Changes to extreme still water level due to surge, El Niño events, and PDOs. (*Source: L. Ewing, 2013*).

Table B-2. General Resources for Determining Still Water Elevation, Surge, El Niño events, and PDOs

Resource	Description	Link
NOAA Sea Level Rise and Coastal Flooding Impacts Viewer	Displays potential future sea levels within wetland areas, and provides visualizations for various amounts of sea level rise. For bays and estuaries, it also provides information on inland areas with the potential to flood if existing barriers to water connectivity are removed or overtopped. Communicates spatial uncertainty of mapped sea level rise, overlays social and economic data onto sea level rise maps, and models potential marsh migration due to sea level rise. Maps do not include any influence of beach or dune erosion.	NOAA Digital Coast, https://coast.noaa.gov/digitalcoast/tools/slr.html
Pacific Institute Sea Level Rise Maps	Downloadable PDF maps showing the coastal flood and erosion hazard zones from the 2009 study. Data are overlaid on aerial photographs and show major roads. Also available are an interactive online map and downloadable maps showing sea level rise and population and property at risk, miles of vulnerable roads and railroads, vulnerable power plants and wastewater treatment plants, and wetland migration potential.	http://www.pacinst.org/reports/sea_level_rise/maps/ For the 2009 report "The Impacts of Sea Level Rise on the California Coast" visit: http://pacinst.org/publication/the-impacts-of-sea-level-rise-on-the-california-coast/
Cal-Adapt – Exploring California's Climate	Represents inundation location and depth for the San Francisco Bay, the Sacramento-San Joaquin River Delta and California coast resulting from different increments of sea level rise coupled with extreme storm events. Incorporates real, time series water level data from past (near 100 year) storm events to capture the dynamic effect of	http://cal-adapt.org/tools/slr-calflod-3d/

	storm surges in modeling inundation using a three dimensional hydrodynamic model (per Radke et al., 2017).	
Regional Sediment Management Plans	Plans for regions of the state to identify how governance, outreach and technical approaches can support beneficial reuse of sediment resources within that region without causing environmental degradation or public nuisance.	http://www.dbw.ca.gov/csmw/

Outcome from Step 3*: Provide estimates of water elevations that can result from surge, El Niño events, and PDOs. When combined with the sea level changes to the tidal range, developed in Step 4, these can provide information on the extreme still water level. For most open coast situations, this information will be used to inform further project analysis and planning that examines erosion, surge and storm conditions.*

Step 4 – Estimate beach, bluff, and dune change from erosion

Predictions of future beach, bluff, and dune erosion are complicated by the uncertainty associated with future waves, storms and sediment supply. As a result, there is no single specific accepted method for predicting future beach erosion. At a minimum, projects should assume that there will be inundation of dry beach and that the beach will continue to experience seasonal and inter-annual changes comparable to historical amounts. When there is a range of erosion rates from historical trends, the high rate should be used to project future erosion with rising sea level conditions (unless future erosion will encounter more resistant materials, in which case lower erosion rates may be used). For beaches that have had a relatively stable long-term width, it would be prudent to also consider the potential for greater variability or even erosion as a future condition. For recent studies that provide some general guidance for including sea level rise in an evaluation of bluff and dune erosion, see, for example, Heberger *et al.* (2009) or Revell *et al.* (2011). Other approaches that recognize the influence of water levels in beach, bluff, or dune erosion can also be used. Table B-3, at the end of this section, provides some resources that can be used for projecting future erosion.

The following sections discuss specific concerns associated with beach, bluff and dune erosion and are provided to acquaint readers to the main issues associated with each system. Readers with a strong background in coastal systems may want to skim or skip the rest of this section.

Beach Erosion

Beach erosion and accretion occur on an on-going basis due to regular variability in waves, currents and sand supply. The movement of sand on and off of beaches is an ongoing process. Along the California coast, periods of gradual, on-going beach change will be punctuated by rapid and dramatic changes, often during times of large waves or high streamflow events.

The overall dynamics of beach change have been described many times.[101] Sand moves on and off shore as well as along the shore. Normal sources of sand to a beach are from rivers and streams, bluff erosion or gullies, and offshore sand sources. Sand leaves a beach by being carried downcoast by waves and currents, either into submarine canyons or to locations too far offshore for waves to move it back onto shore. Beaches are part of the larger-scale sediment dynamics of the littoral cell, and in very simple terms, beaches accrete if more sand comes onto the beach than leaves and beaches erode if more sand leaves than is added. Changes in sand supply are a major aspect of beach change.

Beach changes are often classified as being either seasonal or long-term/inter-annual changes. Seasonal changes are the shifts in beach width that tend to occur throughout the year and are usually reversible. During late fall and winter, beaches tend to become narrower as more high energy waves carry sand away from the beach and deposit it in offshore bars. This is later followed by beach widening as gentler waves again bring sand landward, building up a wider dry-sand summer beach. These changes are considered seasonal changes, and if the beach widths return to the same seasonal width each year, then the beach experiences seasonal changes but no long-term or inter-annual changes. If the seasonal beach widths become progressively wider or narrower, these changes become long-term or inter-annual change, and suggest a long-term beach change trend – accretion if the beach is widening and erosion if the beach is narrowing.

If development is at or near beach level, erosion of the beach can expose the development to damage from waves, flooding, and foundation scour. Additionally, waves that hit the coast bring with them vegetation, floating debris, sand, cobbles, and other material which can act like projectiles, adding to the wave forces and flood damage.

At present, approximately 66% of the California beaches have experienced erosion over the last few decades, with the main concentration of eroding beaches occurring in southern California (Hapke *et al.* 2006). This erosion has been due to a combination of diminished sand supplies and increased removal of sand by waves and currents. With rising sea level, beach erosion is likely to increase due to both increased wave energy[102] that can carry sand offshore or away from the beach, and to decreased supply of new sediments to the coast.[103]

There are several factors that will contribute to the effects of sea level rise on seasonal and inter-annual beach change. There will be the changes to the beach due to inundation by rising water levels, as shown in Figure B-4 (see the discussion on inundation earlier in this Appendix for more information on how to determine this change). If the beach cannot migrate inland to accommodate these changes, then the inundation will result in a direct loss or erosion of beach width. This will result in a narrower seasonal beach as well as inter-annual loss of beach.

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101 See for example, Bascom 1980, Komar 1998, and Griggs *et al.* 2005.

102 In shallow water, wave energy is proportional to the square of the water depth. As water depths increase with sea level rise, wave energy at the same location will likewise increase.

103 Many parts of the developed coast are already experiencing drops in sand supplies due to upstream impoundments of water and sediment, more impervious surfaces, and sand mining.

Seasonal and inter-annual beach conditions will also be affected by changes to waves and sediment supply. Since waves are sensitive to bottom bathymetry, changes in sea level may change the diffraction and refraction of waves as they approach the coast, thereby changing the resulting mixture of beach-accreting and beach-eroding waves. However, the influence of climate change (not just rising sea level) on wave conditions, through changes in wave height, wave direction, storm frequency, and storm intensity, will likely be far more significant than the slight changes from bathymetric changes. In addition, changing precipitation patterns will modify the amount and timing of sediment delivery to the beach.

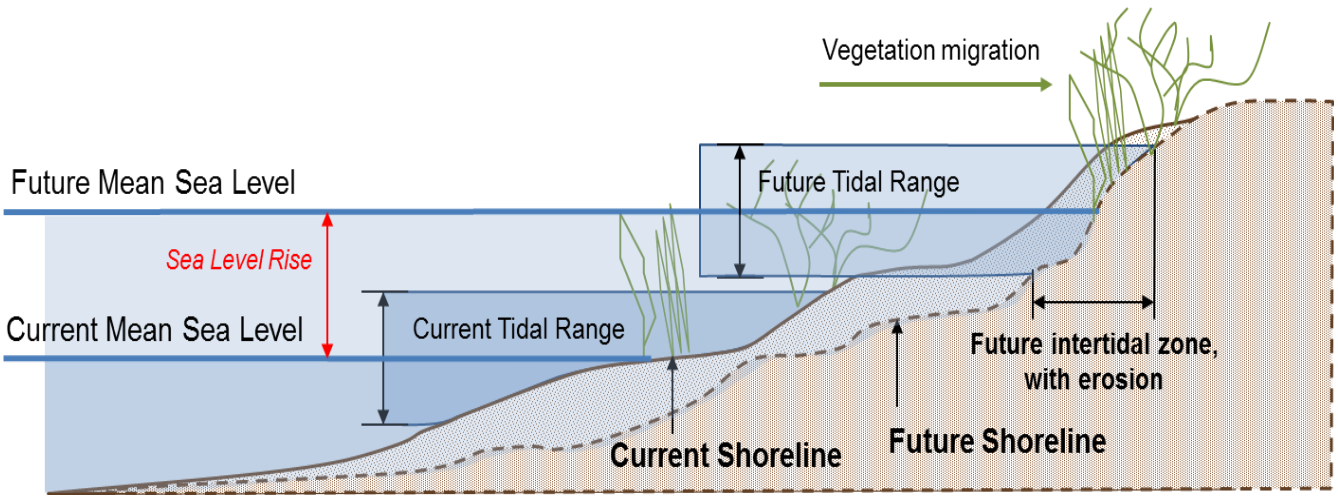

Figure B-4. Changes to the intertidal zone with sea level rise and erosion, without wave impacts. (*Source: L. Ewing, 2013*).

Bluff Erosion

A second type of erosion occurs on coastal bluffs.[104] There is no fully-accepted methodology for estimating future bluff erosion with sea level rise. Guidance for coastal analysts in Hawaii is to assume erosion will increase as a proportion of historical erosion (Hwang 2005). One approach used in the past by the Commission has been to apply one of the higher rates of historical erosion to represent average future trends. A more process-based methodology, used in the Pacific Institute study of erosion due to rising sea level, is to correlate future erosion rates of bluffs with a higher still water level that will allow waves to attack the bluff more frequently (Heberger *et al.* 2009; Revell *et al.* 2011). This approach assumes that all bluff erosion is due to wave impacts and that erosion rates will change over time as the beach or bluff experiences more frequent or more intense wave attack. Such an approach should be considered for examining bluff erosion with rising sea level. Other approaches that recognize the influence of water levels in beach, bluff, or dune erosion can also be used.

[104] Bluffs can be built or expanded during interglacial cycles or following seismic uplift. Many of the marine terraces that are visible along the California coast are remnants of past beach areas that have been uplifted to become bluffs and cliffs. However, natural bluff rebuilding is a millennial or multi-millennial process, and it will not occur during the time periods over which most development projects are evaluated.

Bluff retreat occurs via many different mechanisms. Landslides, slumps, block failures, gullies, and rilling are examples of bluff retreat. At the most basic level, bluff retreat or collapse occurs when the forces leading to collapse of the bluff face are stronger than the forces holding the bluff in place. Forces causing bluff retreat can include earthquakes, wind, burrowing animals, gravity, rain, surface runoff, groundwater, and sheet flow. Coastal bluffs have the added factor of wave attack. Resistance to collapse is mainly a characteristic of the bluff material. For example, granitic bluffs like those along the Big Sur coast retreat at a much slower rate than the soft sandstone and marine terrace bluffs of Pacifica.

Coastal bluff erosion can occur throughout the year, but it often occurs during or after storm periods, when the dry beach will be narrow or non-existent. When coastal bluffs are fronted by wide sand beaches, most waves break on the beach face and the beaches protect the bluffs from direct wave attack. When the beach is narrow, there is less buffering of the wave energy and waves can break directly against the bluffs. A general depiction of bluff retreat with rising sea level is provided in Figure B-5.

Bluff retreat is often episodic – the bluff may be stable for a number of years and then retreat by tens of feet in a few hours or a few days. If the changes to a bluff are examined through endpoint analysis (*i.e.*, looking first at the initial position of the bluff and then at the position of the bluff sometime in the future), researchers can determine the amount of retreat that has occurred during the time from the initial to final positions. This gives information on an average retreat rate that has occurred, but provides no insight about the conditions leading to the retreat, the size of retreat, frequency of retreat events, or the progression of retreat and no retreat. The average retreat rates can give some indication of likely future changes, but they provide little information about when the next retreat episode might occur or how large it might be.

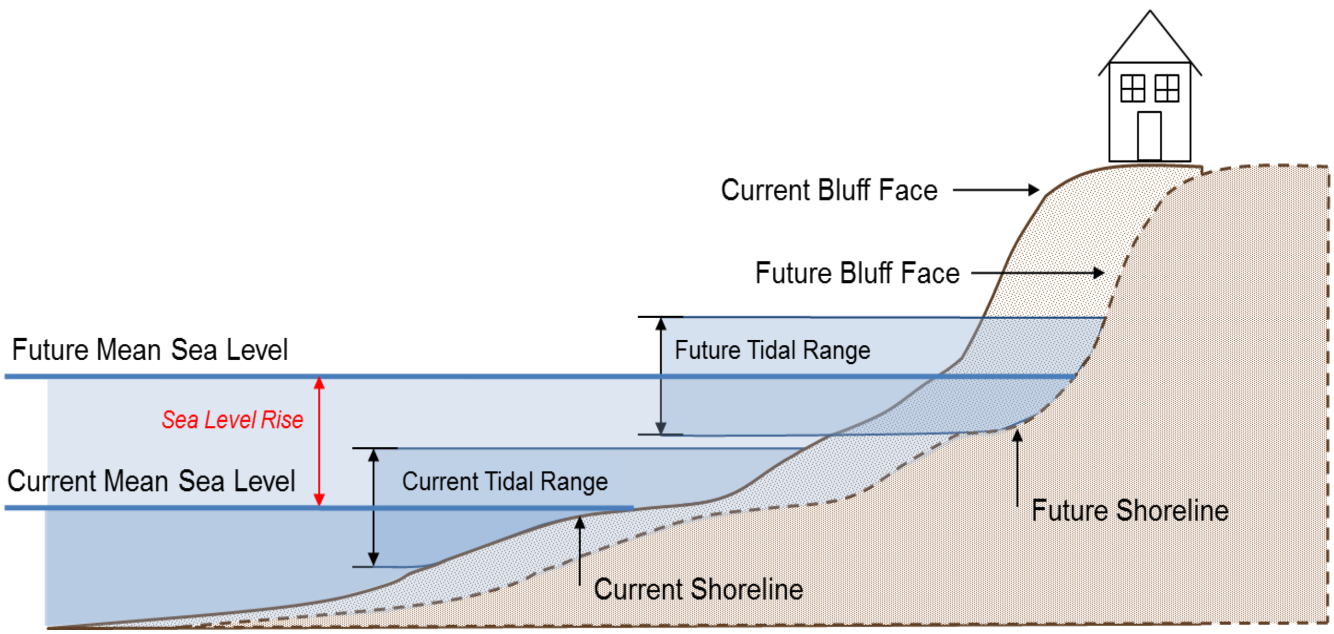

Figure B-5. Bluff erosion with changes in sea level. (*Source: L. Ewing, 2013*).

Dune Erosion

Just as there is no fully-accepted methodology for estimating changes to beach or bluff erosion with sea level rise, there is no fully-accepted methodology for dune erosion. A methodology somewhat similar to that for bluff erosion has been developed for dunes (Heberger *et al.* 2009; Revell *et al.* 2011), and such an approach should be considered for examining dune erosion with rising sea level. Other approaches that recognize the influence of water levels in beach, bluff, or dune erosion may also be used.

Dune erosion occurs when the waves break at or near the dunes, pulling sediment out of the dune. This process deposits sand onto the beach or in the nearshore area, but can result in short-term dune retreat. If sand is not returned to the dunes following these periods of short-term retreat, the sand losses will contribute to long-term dune erosion. Damage will occur to development located on dunes when the dune retreats back to the location of development, either through reversible, short-term retreat or long-term erosion.

For individual cases, determinations of future retreat risk are based on the site-specific conditions and professional analysis and judgment. However, the lack of information about the contributions of all the erosive forces to dunes and the beach-dune interactions makes it challenging to anticipate future changes to coastal dune retreat due to rising sea level and increased wave forces. As with beaches and bluffs for most situations, historical conditions provide a lower limit for future dune *retreat*, or the upper limit of dune *advance* for those sites that are now experiencing accretion or quasi-stability. Projections of future erosion should either: 1) use the high range of historical erosion; 2) develop a sea level rise influenced erosion rate, as done by Heberger *et al.* (2009) or Revell *et al.* (2011); or, 3) develop another approach that considers shoreline changes that are likely to occur under rising sea level conditions.

Table B-3. General Resources for Information on Beach, Bluff and Dune Erosion

Resource	Description	Link
Aerial Photographs	Useful for general information on shoreline trends; ortho-rectified photos can help quantify trends.	California Coastal Records Project, www.californiacoastline.org; Huntington Library; Local Libraries
LIDAR	Fairly detailed topography that can provide GIS layers for current conditions and is comparable with LIDAR data sets for temporal changes.	NOAA's Digital Coast, http://coast.noaa.gov/digitalcoast/data/coastallidar
USGS National Assessment of Shoreline Change with GIS Compilation of Vector Shorelines	Statewide inter-annual beach and bluff erosion; GIS shorelines available for sandy shorelines & cliff edge, showing historical changes for long-term (70 to 100 years) and short-term (25 to 50 years). No projections of future erosion rates available.	Sandy Shorelines – Open File Report 2006-1219, http://pubs.usgs.gov/of/2006/1219, and GIS Data in Open File 2006-1251, http://pubs.usgs.gov/of/2006/1251; Bluff Shorelines – Open File Report 2007-1133, http://pubs.usgs.gov/of/2007/1133, and GIS Data in Open File 2007-1251, http://pubs.usgs.gov/of/2007/1112

Regional Sediment Management Studies	Summaries of seasonal and long-term erosion studies	CSMW Website, http://dbw.ca.gov/csmw/default.aspx; California Beach Erosion Assessment Survey, http://dbw.ca.gov/csmw/library.aspx
US Army Corps of Engineers, Coast of California Studies	Summaries of seasonal and long-term erosion studies	Studies for many regions are available through an internet search (addresses are too numerous to list here)
Beach Profiles and Surveys	Detailed beach or bluff changes with time	NOAA's Digital Coast, https://coast.noaa.gov/digitalcoast/tools/ US Army Corps of Engineers; Regional Beach Studies; University Studies
The Impacts of Sea Level Rise on the California Coast (Pacific Institute Report)	Expected changes to bluff position over time for sea level rise of 4.6 ft (1.4 m) from 2000 to 2100 for California coast from Oregon border through Santa Barbara County.	Pacific Institute Website, http://www.pacinst.org/reports/sea_level_rise/maps/
CoSMoS	Currently available for Point Arena to the Mexico border, with a statewide expansion anticipated in 2018/2019. The Coastal Storm Modeling System (CoSMoS) is a dynamic modeling approach that allows detailed predictions of coastal flooding due to both future sea level rise and storms, and integrated with long-term coastal evolution (i.e., beach changes and cliff/bluff retreat)	https://walrus.wr.usgs.gov/coastal_processes/cosmos/ http://data.pointblue.org/apps/ocof/cms/
TNC Coastal Resilience	An online mapping tool showing potential impacts from sea level rise and coastal hazards designed to help communities develop and implement solutions that incorporate ecosystem-based adaptation approaches. Available statewide with more detailed modelling for Monterey Bay, Santa Barbara, Ventura, and Santa Monica.	http://maps.coastalresilience.org/california/

Outcome from Step 4: *Provide projections of future long-term beach, bluff or dune erosion that takes into account sea level rise. For locations without any influence from storm surge, or wave energy, the identification of the extent of beach, bluff or dune erosion may be sufficient for project analysis and planning efforts. This projected new erosion area may also be useful for anticipating the appropriate setback distance for otherwise stable land forms (If slope stability is a concern, refer to Commission guidance on setbacks (http://www.coastal.ca.gov/W-11.5-2mm3.pdf)). For most open coast situations, this information will be used to inform further project analysis and planning that examines erosion, surge and storm conditions.*

Step 5 – Determine wave, storm wave, wave runup, and flooding conditions

The main concerns with waves, storm waves, and runup are flooding and damage from wave impacts. Flooding is the temporary wetting of an area by waves, wave runup, surge, atmospheric forcing (such as water elevation during El Niño events) and, at river mouths, the combination of waves and river flows. Wave impacts occur when high-energy waves, often associated with storms, reach backshore areas or development. Coastal flooding and wave impacts are worst when they coincide with high water level events (high tide plus high inundation). As sea level rises, inundation will move inland, and so will flooding and wave impacts. Beach erosion will aggravate these conditions and add to the inland extent of impacts.

Flooding

In most situations, factors that result in high water conditions, such as tides, surge, El Niño events, and PDOs, should be used to determine flood levels and flood areas, as shown below. If the area is exposed to storm waves, these forces should be examined as well.

Future Flooding Level = Higher High Tide + Sea Level Rise + Surge + Forcing + Wave Runup

Flooding Areas = Flooding + Seasonal Eroded Beach + Long-Term Beach Erosion

Waves

Waves, like tides, cause constant changes to the water levels that are observed at the coast. The rhythmic lapping of waves on the beach during summer can be one of the joys of a beach visit. At other times of the year, waves can increase in size and energy and damage or destroy buildings, and cause erosion of bluffs and cliffs. Routine ocean waves are generated by wind blowing across the surface of the water and can travel far from their source, combining with waves generated from other locations to produce the rather erratic and choppy water levels that are seen in most of the ocean. As waves move into shallow water and approach land, they are strongly modified by the offshore bathymetry. They take on a more uniform appearance, aligning somewhat parallel to the shoreline through processes of refraction and diffraction. During most of the year, moderate short-period waves break once they are in water depths of approximately 1.3 times the wave height.

Wave impacts depend greatly upon storm activity – both the intensity and the duration of the storm. Normally projects have used design wave conditions comparable to the 100-year event. For critical infrastructure or development with a long life expectancy, it may be advisable to use a greater design standard, such as a 200-year or 500-year event. It may be suitable for some proposed projects to adjust design waves or the frequency of high energy waves to analyze the consequences of worsening wave impacts.

Waves also vary greatly with bathymetry; offshore reefs and sand bars can cause waves to break far from the coast and greatly reduce the energy of the waves that come onshore. Therefore, changes in offshore water depths can alter the nature of nearshore wave propagation and resultant onshore waves. For areas with complex offshore bathymetry, wave impact changes due to rising sea level may need to be examined in the context of both offshore and nearshore conditions.

Wave impacts to the coast, to coastal bluff erosion and inland development, should be analyzed under the conditions most likely to cause harm. Those conditions normally occur in winter when most of the sand has moved offshore leaving only a reduced dry sand beach to dissipate wave energy (this seasonal change in beach width is often referred to as short-term or seasonal erosion). On beaches that will experience long-term erosion, trends expected to occur over the entire expected life of the development should also be considered. Just as the beach conditions to analyze should be those least likely to protect from damage over the life of the development, the water level conditions considered should also be those most likely to contribute to damage over the life of the development. Waves that cause significant damage during high tide will be less damaging during low tide; all other things being equal, waves will cause more inland flooding and impact damage when water levels are higher. Since water levels will increase over the life of the development due to rising sea level, the development should be examined for the amount of sea level rise (or a scenario of sea level rise conditions) that is likely to occur throughout the expected life of the development. Then, the wave impact analysis should examine the consequences of a 100-year design storm event using the combined water levels that are likely to occur with high water conditions and sea level rise, as well as a long-term and seasonally eroded beach.

Eroded Beach Conditions = Seasonal Erosion + Long-Term Erosion*

High Water Conditions = High Tide + Relative Sea Level Rise* + Atmospheric Forcing

Wave Conditions = 100-year Design Storm + High Water + Eroded Beach

* The time period for both long-term erosion and relative sea level rise will be at least as long as the expected life of the development.

The remaining discussion provides general information about waves, the California wave climate, and coastal flooding. It is provided to acquaint readers to the main issues associated with waves and coastal flooding. Readers with a strong background in waves or coastal processes may want to skim or skip the rest of this section.

Storm Waves

During storm conditions, winds can transfer large amounts of energy into waves, increasing wave height, length, and period. Energy transfer to waves depends upon three conditions: the wind energy that is available to be transferred to the water (intensity); the length of time over which the wind blows (duration); and the area over which the wind blows (the fetch). As any of these conditions increases, the energy in the waves will increase, as will the energy that these waves bring to the coastline. Coastal scientists separate waves that are generated far from the coast (swell) from waves that are locally generated (seas). Storms in the mid-Pacific can cause storm-like wave conditions along the coast, even when there are no storms in the area. Likewise, a local storm can cause storm waves along one part of the coast while waves in other sections of the coast may be fairly mild.

Some of the worst storm wave conditions occur when there are intense storms along a large portion of the coast and when this large, distantly generated swell combines with local seas. The 1982/83 El Niño has been cited often as one of the more damaging storm seasons in recent times. In late January 1983, waves from a distant storm combined with locally generated waves and the highest tides of the year. This one storm caused substantial damage along much of the California Coast. The coast was not able to recover before a series of storms in February and March caused additional damage. The full 1982/83 El Niño storm season resulted in damage to approximately 3,000 homes and 900 businesses and destruction of 33 buildings. Damages exceeded $100 million to structures and $35 million to public recreational infrastructure (in 1982 dollars; Flick 1998).

Wave Runup

Wave runup, as depicted in Figure B-6, is the distance or extent to which water from a breaking wave will spread up the shoreline. Much of the wave energy will dissipate during breaking, but wave runup can also be damaging. The runup water moves quickly and can scour or erode the shoreline areas (including the beach), damage structures, and flood inland areas.

Damage from waves and wave runup may increase in the future, due both to rising sea level and to changes in storm intensity and frequency. Waves will break farther landward when water levels are higher. Therefore, increased water levels due to tides, surge, ENSO or PDO variability, or sea level rise will enable more wave energy to reach the beach, back shore, or inland development. The higher water levels do not change the waves. Rather, higher water levels change the point of impact, the extent of runup, and the frequency of wave impact. In locations where high waves now hit the coast, that frequency will increase; in locations where high waves rarely hit the coast, exposure to wave impacts will increase. Increased exposure to wave impacts or wave runup can cause a greater risk of flooding, erosion, bluff failure, and/or damage to development. But, since the focusing of wave energy is strongly influenced by offshore bathymetry, locations of wave exposure may also change with rising sea level and modifications in wave propagation might result from future differences in water depths.

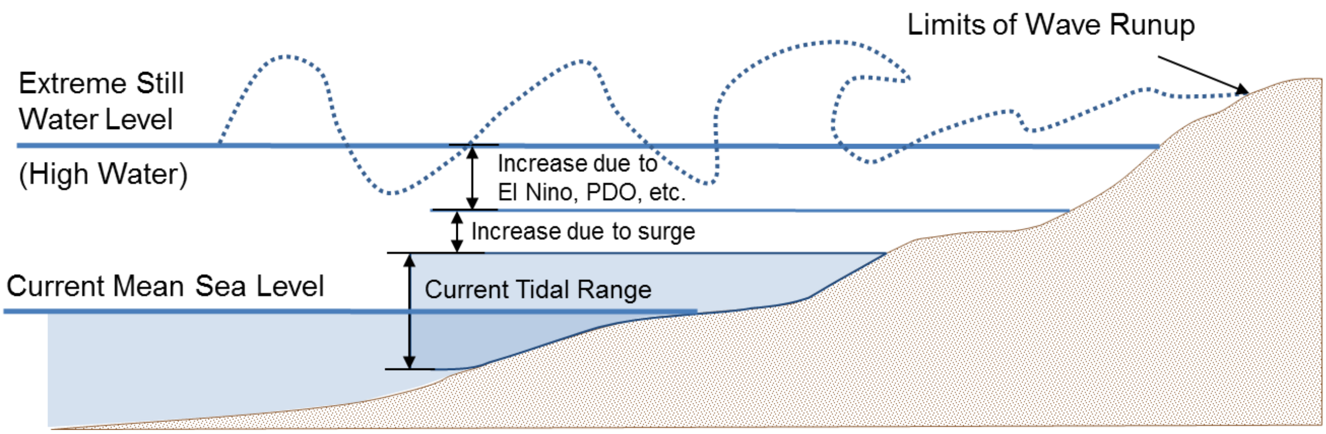

Figure B-6. Wave runup combined with extreme still water (High Water). (*Source: L. Ewing, 2013*).

Summary

Coastal flooding is a significant problem now and it will increase with rising sea level. At present, about 210,000 people in California are living in areas at risk from a 100-year flood event (Heberger *et al.* 2009). A rise in sea level of 55 in (1.4 m) with no change in development patterns or growth along the coast could put 418,000 to 480,000 people at risk from a 100-year flood (Cooley *et al.* 2012). An additional fraction of the California population that relies on critical infrastructure located in potentially hazardous areas is also vulnerable and increases in storm intensity or in the density of development in flood-prone areas will increase the number of people at risk from flooding.

The frequency and intensity of high wave events depends upon the storm conditions that generate the waves. There is less consistency in the output of climate models related to projections of future storm conditions than there has been for temperature projections. A recent report on coastal flooding from years 2000 to 2100 for the California coast has found that “storm activity is not projected to intensify or appreciably change the characteristics of winter nearshore wave activity of the twenty-first century” (Bromirski *et al.* 2012, p. 33). This continuation of current storm conditions is not, however, an indication that storms will not be a problem in the future. Storm damage is expected to continue, and, if sea level rise by the end of the twenty-first century reaches the high projections of about 55 in (1.4 m), “coastal managers can anticipate that coastal flooding events of much greater magnitude than those during the 1982-83 El Niño will occur annually.” (Bromirski *et al.* 2012, p. 36)

For most situations, the 100-year storm event should be used as the design storm. This is equivalent to a storm with a 1% annual probability of occurrence. However, most development does outlast one year and this probability of occurrence grows over time such that there is a 22% probability of occurrence during a 25-year period and over 53% probability that this storm will occur at least once during a 75-year period. Even so, the 100-year storm event, like the 100-year flood event, is often used as a design standard for development. However, for structures with a very long projected life or for which storm protection is very critical, a larger, 200-year or 500-year event might be appropriate.

Table B-4 lists many of the resources that are available for finding regional or state-wide information on waves and flooding. Local communities may have records of major erosion episodes or flood events as well.

Table B-4. General Resources for Flooding and Wave Impacts

Resource	Description	Link
CDIP (Coastal Data Information Program)	Current and historical information on wind, waves, and water temperature, wave and swell models and forecasting. As of 2013, there are 19 active stations along the California coast.	http://cdip.ucsd.edu/
Flood Insurance Rate Maps (FIRMs)	FEMA is updating coastal flood maps. Existing FIRMs are based on 1980s topography; flooding includes seasonal beach change but not long-term erosion. Maps do not include sea level rise. Inclusion of a site shows a flood hazard; but exclusion does not necessarily indicate a lack of flood hazard.	FEMA Flood Map Service Center, https://msc.fema.gov/portal
FEMA Flood Hazard Mapping Guidance	*Subsection D.2.8* provides guidance for calculating wave runup and overtopping on barriers. There are special cases for steep slopes and where runup exceeds the barrier or bluff crest.	https://www.fema.gov/media-library/assets/documents/13948
Regional Sediment Management Studies	Some studies show elements of beach flooding and wave impacts.	http://dbw.ca.gov/csmw/default.aspx
Cal-Adapt – Exploring California's Climate	Represents inundation location and depth for the San Francisco Bay, the Sacramento-San Joaquin River Delta and California coast resulting from different increments of sea level rise coupled with extreme storm events. Incorporates real, time series water level data from past (near 100 year) storm events to capture the dynamic effect of storm surges in modeling inundation using a three dimensional hydrodynamic model (per Radke et al., 2017).	http://cal-adapt.org/tools/slr-calflod-3d/
US Army Corps of Engineers, Coastal Engineering Manual	Detailed information on all aspects of deep-water wave transformation, shoaling, runup, and overtopping.	https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/
European Overtopping Manual	Descriptions of available methods for assessing overtopping and its consequences. Provides techniques to predict wave overtopping at seawalls, flood embankments, breakwaters and other shoreline structures facing waves. Supported by web-based programs for the calculation of overtopping discharge and design details.	http://www.overtopping-manual.com/

CoSMoS	Currently available for Point Arena to the Mexico border, with a statewide expansion anticipated in 2018/2019. The Coastal Storm Modeling System (CoSMoS) is a dynamic modeling approach that allows detailed predictions of coastal flooding due to both future sea level rise and storms, and integrated with long-term coastal evolution (i.e., beach changes and cliff/bluff retreat)	https://walrus.wr.usgs.gov/coastal_processes/cosmos/ http://data.pointblue.org/apps/ocof/cms/
TNC Coastal Resilience	An online mapping tool showing potential impacts from sea level rise and coastal hazards designed to help communities develop and implement solutions that incorporate ecosystem-based adaptation approaches. Available statewide with more detailed modelling for Monterey Bay, Santa Barbara, Ventura, and Santa Monica.	http://maps.coastalresilience.org/california/

Outcome from Step 5: *Provide projections of future flooding and wave impacts resulting from waves, storm waves and runup, taking into account sea level rise.*

Step 6 – Examine potential flooding from extreme events

Extreme events[105], by their very nature, are those beyond the normal events that are considered in most shoreline studies. Examples of extreme events that might occur along the California coast include:

- An individual storm with an intensity at or above the 100-year event
- A series of large, long-duration storms during high tides
- A local storm that coincides with the arrival of distant swell and high tides
- Rapid subsidence, as might happen along the Northern California coast during a Cascadia Subduction Zone earthquake
- Global sea level rise greater than that projected to occur by 2100, when combined with a large storm during normal tides

Planning and project analysis need to consider and anticipate the consequences of these outlier events. In many situations, this assessment might be a qualitative consideration of consequences that could happen if an extreme event does occur. Analysis of the consequences of extreme events presents opportunities to address some of those potential impacts through design and adaptation.

[105] In its report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, the IPCC defines extreme events as "a facet of climate variability under stable or changing climate conditions. They are defined as the occurrence of a value or weather or climate variable above (or below) a threshold value near the upper (or lower) ends ("tails") of the range of observed values of the variable" (IPCC 2012).

In California, there may be some worsening of extreme precipitation and inland flooding from projected changes to atmospheric rivers, narrow bands of concentrated moisture in the atmosphere. In general, however, future extremes are likely to be comparable to the extremes of today, but with the added influence of sea level rise. Extreme storm waves or floods can be addressed with the guidance provided earlier, except that the extreme storm conditions would be used. For tsunamis it is recommended that, for most situations, the appropriate projection of sea level rise be added to the currently projected inundation level from tsunamis. This will provide a close approximation for future inundation from extreme tsunamis. If a detailed analysis of future tsunami impacts is needed, the analysis should be conducted by someone experienced in modeling tsunami waves.

Tsunamis

Tsunamis are large, long-period waves that can be generated by submarine landslides, subaerial landslides (slope failures from land into a water body), large submarine earthquakes, meteors, or volcanic eruptions. They are rare events, but can be extremely destructive when they occur. The extent of tsunami damage will increase as rising water levels allow tsunami waves to extend farther inland. Thus the tsunami inundation zone will expand inland with rising sea level. There has been no research that suggests that climate change will increase the intensity or frequency of seismically-generated tsunamis. However, the number and size of coastal subaerial landslides may increase because of increased coastal erosion due to sea level rise, which in turn may increase the potential for tsunamigenic landslides along the California coast (Highland 2004; Walder *et al.* 2003).

The detailed changes to the inundation zone with rising sea level need to be determined by modeling; however, modeling of long-waves, such as tsunamis, is a specialized area of coastal engineering, and will not be covered in this general Guidance. For most situations, it will be sufficient to get information on possible inundation from the most recent tsunami inundation maps (currently on the Department of Conservation website, http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Inundation_Maps/Pages/Statewide_Maps.aspx). The California Geological Survey and California Governor's Office of Emergency Services are creating new tsunami inundation maps based on probabilistic tsunami hazard analysis (CPTHAWG 2015). As a rough approximation, the change to the tsunami inundation level can be estimated as equal to the change in water elevation due to sea level; a 1-ft rise in sea level could be assumed to result in a 1-ft rise in the inundation elevation. However, in many places, particularly shallow bays, harbors, and estuaries, the change in tsunami inundation zone is likely to scale non-linearly with sea level rise and require careful modeling. California Geological Survey is also working to evaluate the impact of sea level rise with numerical tsunami modeling to verify that an additive approach (tsunami height + SLR) is the appropriate method for integrating SLR and tsunami inundation together. In areas with high tsunami hazards, or where critical resources are at risk, a site-specific analysis of sea level rise impacts on tsunami hazards is crucial, and someone experienced in modeling tsunami waves should be consulted.

Summary

Many different factors affect the actual water levels that occur along the coast and resulting hazards. In California, waves and tides have the largest routine effect on water levels. Tsunamis may have a very large, but infrequent effect on water levels. Sea level rise will affect water levels all along the coast. Until the mid-century, tides and storms are expected to have the biggest effects on local water levels, with sea level rise being a growing concern. After Year 2050, sea level rise is expected to become increasingly influential on water levels and in contributing to damages to inland areas from flooding, erosion and wave impacts. Table B-5 provides a general characterization of all the factors that can affect local water levels, with general estimates of their range and frequency of occurrence.

Outcome from Step 6: *Projections of potential flooding from extreme events including rapid subsidence, extreme precipitation, and tsunamis.*

Table B-5. Factors that Influence Local Water Level Conditions

Factors Affecting Water Level	Typical Range for CA Coast (ft)	Typical Range for CA Coast (m)	Period of Influence	Frequency
Tides	3 – 10	1 – 3	Hours	Twice daily
Low pressure	1.5	0.5	Days	Many times a year
Storm Surge	2 – 3	0.6 – 1.0	Days	Several times a year
Storm Waves	3 – 15	1 – 5	Hours	Several times a year
El Niño events (within the ENSO cycle)	<1.5	< 0.5	Months - Years	2 – 7 years
Tsunami waves	20 – 50 (max) 3 – 10 (typical)	6 – 15 (max) 1 – 3 (typical)	Minutes, Hours, Days	Infrequent but unpredictable
Historical Sea Level, over 100 years	0.7	0.2	Ongoing	Persistent
OPC Sea Level Projections 2000 – 2050 (SF tide gauge; see also App. G)	1.1 – 2.7	0.3 – 0.8	Ongoing	Persistent
OPC Sea Level Projections 2000 – 2100 (SF tide gauge; see also App. G)	3.4 – 10.2	1.0 – 3.1	Ongoing	Persistent

Note that all values are approximations. The conversions between feet and meters have been rounded to maintain the general ranges and they are not exact conversions. *Sources*: Flick 1998; OPC 2018; Personal communications from Dr. Robert Guza (Scripps Institution of Oceanography), Dr. William O'Reilly (Scripps Institution of Oceanography and University of California, Berkeley), and Rick Wilson, California Geological Survey; and professional judgment of staff.

REFERENCES: APPENDIX B

Bascom W. 1979. *Waves and Beaches: The Dynamics of the Ocean Surface.* Garden City, NY: Anchor Books. 366pp.

Bromirski PD, AJ Miller, RE Flick, G Auad. 2011. Dynamical suppression of sea level rise along the Pacific Coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research-Oceans* 116: C07005. doi:10.1029/2010JC006759.

Bromirski PD, DR Cayan, N Graham, RE Flick, M Tyree. 2012. White Paper from the California Energy Commission. Prepared by Scripps Institution of Oceanography, CEC-500-2012-011. http://www.energy.ca.gov/2012publications/CEC-500-2012-011/CEC-500-2012-011.pdf.

California Probabilistic Tsunami Hazard Analysis Work Group (CPTHAWG). 2015. *Evaluation and Application of Probabilistic Tsunami Hazard Analysis in California – Phase 1: Work Group Review of Methods, Source Characterization, and Applications to the Crescent City Demonstration Project Results.* California Geological Survey Special Report 237. 33 pp. http://activetectonics.coas.oregonstate.edu/paper_files/reports/012615_CGS%20Special%20Report%20237-Evaluation%20of%20Probabilistic%20Tsunami%20Hazard%20Analysis%20in%20California-final.pdf.

Cayan DR, PD Bromirski, K Hayhoe, M Tyree, MD Dettinger, RE Flick. 2008. Climate change projections of sea level extremes along the California coast. *Climatic Change* 87(Suppl 1): S57-S73. doi:10.1007/s10584-007-9376-7.

Cooley H, HE Moore, M Heberger, L Allen. 2012. *Social Vulnerability to Climate Change in California*. White paper from the California Energy Commission. Prepared by the Pacific Institute. CEC-500-2012-013. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.260.471&rep=rep1&type=pdf.

Flick RE. 1998. Comparison of California tides, storm surges, and mean sea level during the El Niño winters of 1982–1983 and 1997–1998. *Shore & Beach* 66(3): 7-11.

Flick R, J Murray, L Ewing. 2003. Trends in U.S. Tidal Datum Statistics and Tide Range. *ASCE Journal of Waterway, Port, Coast and Ocean Engineering* 129(4): 155-164. http://dsp.ucsd.edu/~jfmurray/publications/Flick2003.pdf.

Gallien TW, PL Barnard, M van Ormondt, AC Foxgrover, BF Sanders. 2012. A parcel-scale coastal flood forecasting prototype for a southern California urbanized embayment. *Journal of Coastal Research* 29(3): 642-656. doi: 10.2112/JCOASTRES-D-12-00114.1.

Gallien TW, JE Schubert, BF Sanders. 2011. Predicting tidal flooding of urbanized embayments: A modeling framework and data requirements. *Coastal Engineering* 58(6): 567-577. doi:10.1016/j.coastaleng.2011.01.011.

Griggs G, K Patsch, L Savoy (Eds.). 2005. *Living with the Changing California Coast*. Berkeley and LA, CA: University of California Press. 551 pp.

Grinsted A, J Moore, S Jevrejeva. 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics* 34: 461-472. doi:10.1007/s00382008-0507-2.

Hapke CJ, D Reid, BM Richmond, P Ruggiero, J List. 2006. *National Assessment of Shoreline Change Part 3: Historical Shore Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast*. USGS Open File Report 2006-1219.

Heberger M, H Cooley, P Herrera, PH Gleick, E Moore. 2009. *The Impacts of Sea-Level Rise on the California Coast*. Prepared by the Pacific Institute for the California Climate Change Center. http://dev.cakex.org/sites/default/files/CA%20Sea%20Level%20Rise%20Report.pdf.

Highland L. 2004. *Landslide Types and Processes*. US Geological Survey Fact Sheet 2004-3072: 1-4, Reston, VA.

Hwang DJ. 2005. *Hawaii Coastal Hazard Mitigation Guidebook*. University of Hawaii Sea Grant College Program. 216 pp.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change.* [S Solomon, D Qin, M Manning, M Marquis, K Averyt, MMB Tignor, HL Miller, Jr., Z Chen (eds.)], Cambridge University Press: Cambridge, UK and New York, NY, USA. 91 pp. https://www.ipcc.ch/report/ar4/

Intergovernmental Panel on Climate Change (IPCC). 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [CB Field, V Barros, TF Stocker, D Qin, DJ Dokken, KL Ebi, MD Mastrandrea, KJ Mach, GK Plattner, SK Allen, M Tignor, PM Midgley (Eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA. 582 pp. http://ipcc-wg2.gov/SREX/report/.

Jevrejeva S, JC Moore, A Grinsted. 2012. Sea level projections to AD2500 with a new generation of climate change scenarios. *Global and Planetary Change* 80-81: 14-20. doi:10.1016/j.gloplacha.2011.09.006.

Komar PD. 1998. *Beach Processes and Sedimentation*. 2nd Ed. Upper Saddle River, NJ: Prentice Hall. 544pp.

Kopp R, F Simons, J Mitrovica, A Maloof, M Oppenheimer. 2009. Probabilistic assessment of sea level during the last interglacial stage. *Nature* 462: 863-867. doi:10.1038/nature08686.

Merrifield MA. 2011. A shift in western tropical Pacific sea level trends during the 1990s. *Journal of Climate* 24(15): 4126-4138. doi:10.1175/2011JCLI3932.1.

National Research Council (NRC). 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Report by the Committee on Sea Level Rise in California, Oregon, and Washington. National Academies Press, Washington, DC. 250 pp. http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington.

Nicholls RJ, N Marinova, JA Lowe, S Brown, P Vellinga, D de Gusmao, J Hinkel, RSJ Tol. 2011. Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Philosophical Transactions of the Royal Society* 369(1934): 161-181. doi:10.1098/rsta.2010.0291.

National Oceanic and Atmospheric Administration (NOAA) Tides and Currents. 2013. *Center for Operational Oceanographic Products and Services.* Retrieved 19 July, 2013, from http://tidesandcurrents.noaa.gov/.

Ocean Protection Council (OPC). 2018. *State of California Sea-Level Rise Guidance: 2018 Update.* *http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf*

Pfeffer WT, JT Harper, S O'Neel. 2008. Kinematic constraints on glacier contributions to 21st century sea-level rise. *Science* 321(5894): 1340 -1343. doi:10.1126/science.1159099.

Rahmstorf S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* 315(5810): 368-370. doi:10.1126/science.1135456.

Revell DL, R Battalio, B Spear, P Ruggiero, J Vandever. 2011. A methodology for predicting future coastal hazards due to sea-level rise on the California Coast. *Climatic Change* 109(Suppl 1): 251-276. doi:10.1007/s10584-011-0315-2.

Rohling E, K Grant, C Hemleben, M Siddall, B Hoogakker, M Bolshaw, M Kucera. 2008. High rates of sea-level rise during the last interglacial period. *Nature Geoscience* 1: 38-42. doi:10.1038/ngeo.2007.28.

Schaeffer M, W Hare, S Rahmstorf, M Vermeer. 2012. Long-term sea-level rise implied by 1.5˚C and 2˚C warming levels. *Nature Climate Change* 2: 867-870. doi:10.1038/nclimate1584.

Schubert JE, BF Sanders. 2012. Building treatments for urban flood inundation models and implications for predictive skill and modeling efficiency. *Advances in Water Resources* 41: 49-64. doi:10.1016/j.advwatres.2012.02.012.

Vellinga P, C Katsman, A Sterl, J Beersma, W Hazeleger, J Church, R Kopp, D Kroon, M Oppenheimer, H Plag, S Rahmstorf, J Lowe, J Ridley, H von Storch, D Vaughan, R van de Wal, R Weisse, J Kwadijk, R Lammersen, N Marinova. 2009. *Exploring high-end climate change scenarios for flood protection of the Netherlands. International Scientific Assessment*, Prepared for the Delta Committee. Scientific Report WR-2009-05. KNMI, Alterra, The Netherlands. 150pp. http://edepot.wur.nl/191831.

Vermeer M, S Rahmstorf. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Science* 108: 21527-21532. doi:10.1073/pnas.0907765106.

Walder JS, P Watts, OE Sorensen, K Janssen. 2003. Tsunamis generated by subaerial mass flows. *Journal of Geophysical Research: Solid Earth (1978–2012)* 108: B5. doi: 10.1029/2001JB000707.