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

This Appendix provides technical information addressing how to determine local hazard conditions for sea level rise planning efforts. This process is described more broadly as Steps 1-4 in Chapters 5 and 6 in this document and includes determining a range of sea level rise scenarios and analyzing the physical effects and possible resource impacts of sea level rise hazards.

This appendix provides an overview of the physical effects of sea level rise on coastal hazards and other physical processes. The appendix is organized by the most commonly considered coastal hazards and physical processes and will describe how sea level rise is expected to influence them into the future. Similarly, each section will describe how sea level can be considered in assessments for each coastal hazard or physical process.

It can be challenging to "right size" analyses that look to identify the physical effects of sea level rise. Screening level analyses can be useful to identify the types of hazards that may need to be more closely evaluated, for example with more detailed modeling or analysis, in certain areas. As discussed in more detail in Chapters 5 and 6, it is a good idea to reach out to Coastal Commission Staff early in the process to advise on what level of hazards analyses may be recommended for different planning or permitting processes.

Water level varies locally, so these analyses 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 2024 State Sea Level Rise Guidance (OPC 2024) 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.

Sea level rise raises the background water level from which many more dynamic changes start. Sea level rise will have many physical effects, some of which will increase non-linearly, such as the amount of wave energy that reaches California's coastlines. The following box identifies some of the key situations in which it is important for coastal managers and applicants to consider sea level rise during planning or project reviews.

General situations needing sea level rise analysis include when the project site or planning area 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
- Shown as exposed to hazards on a SLR viewer such as COSMOS under the 2.0m SLR scenario

The following coastal hazards and other physical processes are some of the more commonly considered hazards for planning and development in coastal areas in the State. These are described in more detail in the following sections.

- Coastal erosion
- Wetland change
- Coastal flooding
- Fluvial/riverine flooding
- Pluvial/stormwater flooding
- Groundwater rise
- Tsunamis

Coastal Erosion

The coast is shaped by the powerful forces from waves, currents, rainfall, and wind. This section will describe the effects of sea level rise on beach change and bluff erosion.

Beach Change

Beaches are highly dynamic and respond to changes in sediment inputs and wave conditions. Beaches change on a variety of timescales. It can be useful to think about the timescales of this change as long-term, decadal, seasonal, and storm event-driven.

Beaches can be understood generally to be in equilibrium with sea level. As sea level rises, beaches will generally shift upward (vertically) and recede landward (horizontally), proportional to the slope of the beach. This concept is generally known as the Bruun Rule. It involves several key assumptions, including that, at equilibrium, the shape of the beach profile is maintained through time, that sand transport into and out of the area of interest is constant, that the upper beach is eroded as the shore profile moves landward, and that the eroded material is deposited offshore to reestablish the equilibrium profile – meaning that the Bruun Rule assumes an erodible backshore as opposed to, for example, a seawall. As sea level rise accelerates, the retreat of beaches due to the Bruun Rule is expected to become an increasingly large factor in beach change.

There are several approaches to evaluating the potential for beach erosion for the purposes of planning and development. The level of complexity in terms of the processes considered as well as the data and skill needed for analysis varies greatly.

One of the simplest approaches to estimating beach change is to examine long-term shoreline trends. This can be done by looking at historical imagery. Recent advances in the processing of satellite data have opened up large datasets of historic shoreline change, such as CoastSat, that can also be useful for identifying long-term trends. Similarly, looking at historic observed seasonal or event-driven changes can be useful for estimating the potential range of shoreline positions that might be observed beyond long-term shifts in mean shoreline position. Notably, just evaluating historic trends alone will not adequately account for the effects of future sea level rise. Observed trends can be combined with the retreat estimated by the Bruun Rule or other similar equilibrium models.

One of the more comprehensive tools for looking at long-term beach change is the CoSMoS Coastal One-line Assimilated Simulation Tool (CoSMoS-COAST). The CoSMoS-COAST tool uses historic shoreline change data to calibrate a shoreline change model that takes into account many of the easier-to-measure factors that contribute to beach change. These include Bruun Rule recession, longshore drift, and cross-shore beach change. Sand supply, a major factor in beach change, is not explicitly considered due to the difficulty in projecting changes to sand supply; however, observed long-term erosional or accretional trends not explained by the more easily forecastable factors are assumed to continue in the future. While CoSMoS-COAST includes considerable uncertainty, this uncertainty is quantified. CoSMoS-COAST is also available at a 100-meter resolution for all open coast beaches statewide which makes it a powerful tool for evaluating future beach change.

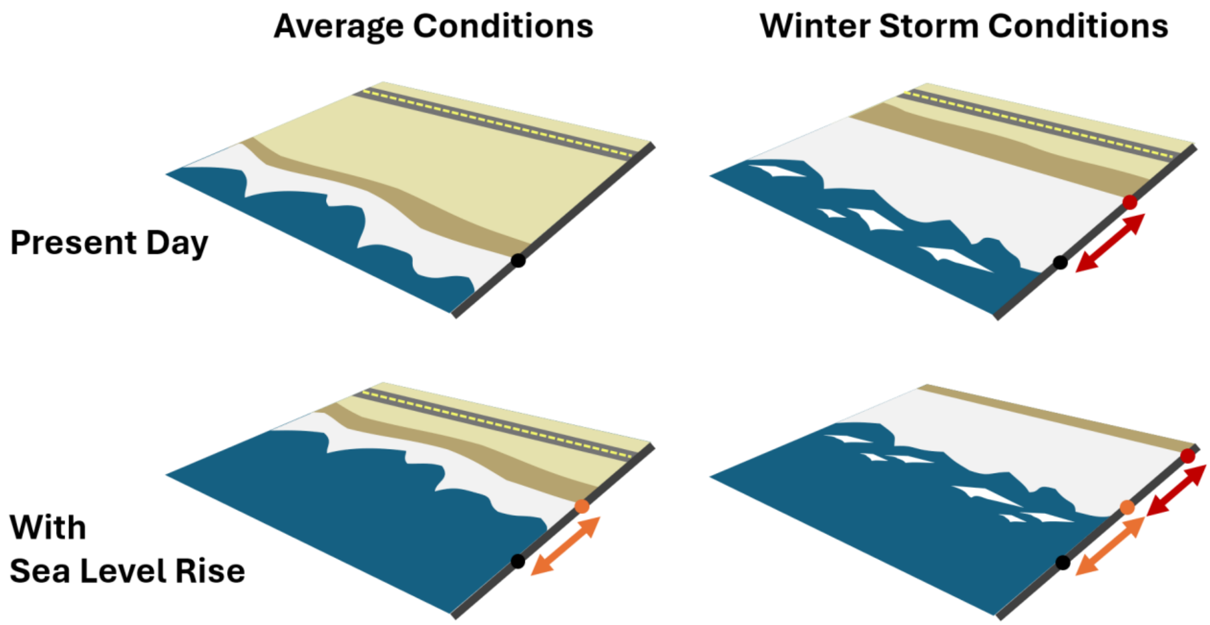

Figure B-1. Diagram showing beach erosion from both sea level rise and winter storm conditions (Source: J. Smith, 2024)

Bluff Erosion

California has a diversity of coastal bluffs which will, in general, continue to erode over time. The rate of a retreat of a coastal bluff is closely related to its geologic composition and the erosional processes at work in a given location. Bluffs composed of hard, resistant bedrock will erode slowly compared to bluffs with a base of relatively weak and poorly cemented terrace deposits. Coastal bluff erosion is also driven by a variety of factors including both marine (e.g., wave attack and wave spray) and subaerial processes (e.g., intense rainfall and runoff). In general, sea level rise will intensify marine erosion by increasing the frequency and force and wave attack at the base of coastal bluffs. For example, with sea level rise, some bluffs that are currently protected by wide sandy beaches and seldom experience significant wave attack may start to erode more quickly when higher water levels or beach erosion causes the frequency and intensity of wave attack to increase.

Long-term historical trends in bluff retreat provide an important indicator of the potential for future bluff erosion with sea level rise. Similar to beach change, past bluff retreat can be estimated through the use of historical aerial imagery. However, bluff retreat is often episodic. In other words, bluffs can remain unchanged for sustained periods then fail and erode relatively rapidly. As a result, a significant amount of time (ideally as long as possible) is often needed to be able to determine long-term average erosional trends for coastal bluffs. There have been several efforts to develop statewide retreat rates for coastal bluffs with varying levels of associated uncertainty and spatial resolution. Some of the most commonly referenced datasets include Hapke & Reid, 2007, which uses georeferenced historical maps and aerial imagery, and Swirad and Young, 2022, which uses airborne LiDAR.

There are several approaches available to estimate how bluff retreat would be accelerated by sea level rise. As part of the work done by USGS for their CoSMoS Cliff Retreat tool, Limber *et al*., 2018, summarize several modeling approaches. One model bluff retreat, an extension of the Bruun Rule discussed above, assumes coastal bluffs are in equilibrium with their fronting beaches and that, with sea level rise, bluff erosion will accelerate in relation to both the shape of the beach profile and amount of beach-quality sediment the bluffs would provide to the beach profile as they erode. Another model assumes that the bluff retreat rate will increase in proportion to the frequency with which waves are able to runup and reach the toe of the bluff with sea level rise. Other models accelerate cliff erosion in proportion to increases in the rate of sea level rise, with options to select the relationship (linear or exponential) between the rate of sea level rise and the bluff erosion response. Still other models relate bluff erosion rates to sea level driven changes in wave energy, the force delivered at the bluff toe, and fronting beach widths. While no single modeling approach can capture all the factors governing how coastal bluffs will respond to sea level rise, these modeling approaches can provide insight into the range of potential outcomes under different sea level rise scenarios.

USGS developed bluff retreat projections statewide using an ensemble of multiple bluff retreat models (some of which are outlined above) for four sea level rise scenarios (CoSMoS-Cliff). The calibrated, but unvalidated, ensemble includes five simple models that project bluff retreat from historical bluff retreat, wave impacts, sea level rise, and the geometry of the shore profile. The projections are available at a spatial resolution of 100 meters, though projections are meant to project time-averaged, multidecadal bluff retreat over large spatial scales. These projections are valuable for community-scale hazards analyses and land use planning, though more detailed analyses are often needed for site-specific analyses, including those used for siting and design of individual development projects.

Most models and tools used for bluff retreat project the long-term time-averaged retreat of a bluff's edge. However, as mentioned previously, bluff retreat typically occurs episodically, with retreat sometimes occurring on the order of tens of feet in a single event, followed by extended periods with little retreat. For this reason, it is critical that development setbacks from bluff edges consider the potential magnitudes of episodic erosion or failure events in addition to long-term, average retreat rates. This can be done through looking at past bluff failure events or analyzing slope stability (e.g., determining the failure plane of a slope with a 1.5 factor of safety).

Additional Considerations

Additionally, there are several important considerations when evaluating the potential for coastal erosion as influenced by sea level rise. Sandy beaches may have significant deposits of coarser material, such as cobble, which may change both their response to seasonal erosion and long-term responses to sea level rise. Beaches may also exist as a relatively thin layer of sand above high bedrock platforms which may influence both their ability to persist in the future (if these platforms form a steep and erosion resistant backshore) as well as how the beaches respond to seasonal forcing from waves. Also, developed backshores can sometimes be made of highly erodible fill material with high percentages of fines which may lead to accelerated erosion, particularly as shorelines retreat and expose these backshores to more frequent storm wave activity.

Sand dunes are also an important part of many beach systems. Dunes can vary greatly in both size and dynamics. Natural dunes in addition to engineered dune or dune-like systems can provide significant flood reduction benefits in addition to being an important source of sand to beaches during erosive events. Portions of dune systems can also be highly dynamic, like beaches, and are also expected to shift upward and inland with sea level rise under equilibrium conditions. Where dunes are a significant part of the shore or where they are being proposed as strategies to address hazards, particular care should be taken to incorporate dune change as part of estimates of coastal erosion.

Coastal Wetland Change

Coastal wetlands such as mudflats and saltmarshes are affected by the way sediment moves in and through estuarine systems. Intertidal features and habitats are very sensitive to water levels and will change with sea level rise (Spencer *et al.*, 2016).

Different levels of analysis for evaluating coastal wetland change vary in the amount of data and skill required. Much of this variation comes from how or if changes to landforms are considered. Figure B-2 illustrates how sea level rise will shift the tidal range vertically and vegetated areas may shift in response to both future water levels and changes in landforms.

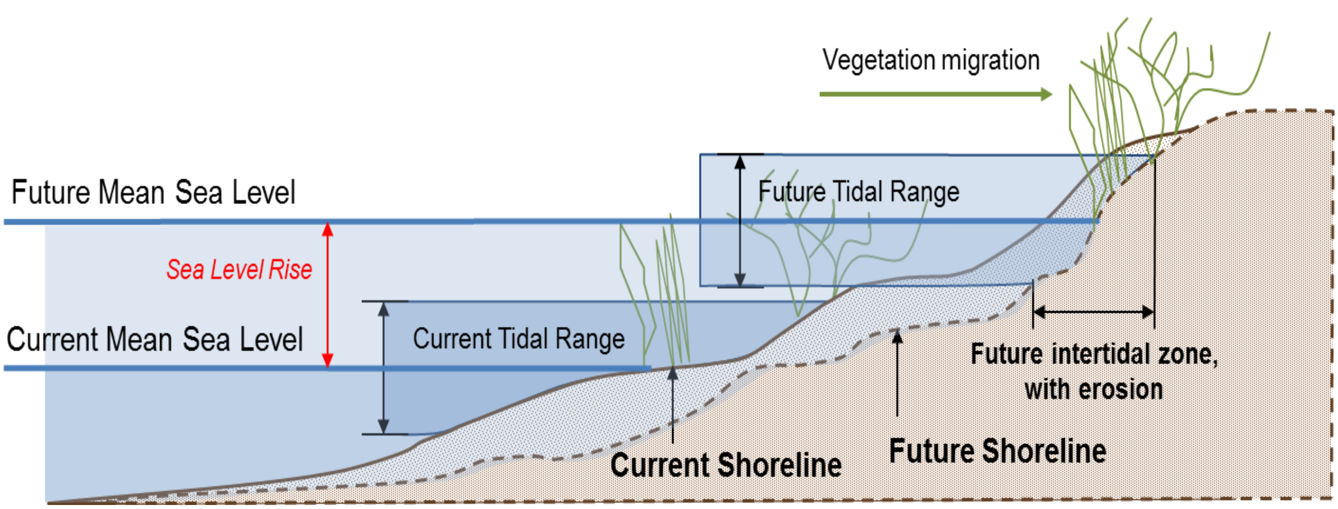

Figure B-2. Changes to the intertidal zone with sea level rise and erosion, without wave impacts. (Source: L. Ewing, 2013).

The simplest approach to evaluating coastal wetland change is to assume landforms remain the same and habitats will re-equilibrate to changing sea levels. In some wetlands, landform change can be dramatic even over short time periods (**Fig.** B-3). As mentioned previously, coastal wetlands are very sensitive to water levels and their distribution is largely controlled by the elevation of land relative to the local tide range. While sea level rise may change the range of the tides in certain areas, it is often simpler and sufficiently accurate to assume this change will not be significant and simply shift the existing tide range vertically by the amount of sea level rise being analyzed.

Figure B-3. Photo series documenting rapid bank and wetland erosion in Elkhorn Slough (adapted from California Department of Fish and Wildlife, 2021 with additional photo from B. Ammen, 2023)

More complex approaches would include creating a hydrodynamic model that simulates the water levels and currents that can then be used to model the movement of sediment and vertical erosion or accretion that may change landforms in an estuarine system. These kinds of models often require significant effort to develop, calibrate, and validate but can be used to answer specific management questions such as which coastal wetland areas may have sufficient natural sediment supplies to be able to keep pace with sea level rise and which areas may need more significant management actions to preserve ecosystem functions.

When deciding how to estimate coastal wetland change considering sea level rise, an initial assessment should consider how stable landforms have been within recent history, why landforms have or have not changed (for example, considering if existing marshes are in equilibrium with current sediment supply or tidal currents), and then evaluate whether it is reasonable to assume those factors would continue unchanged into the future with sea level rise.

COASTAL FLOODING

Extreme water levels are caused by a combination of high tides, storm surge, oceanographic forcing, and waves. Along the open coast of California, waves are typically, if not always, a major factor in driving extreme water levels and coastal flooding. The biggest storm waves often come from "swell" which originates far out in the Pacific Ocean. In sheltered areas where there is sufficient "fetch," wind waves can become sizeable enough to warrant consideration in analyses.

The deeper the water close to shore, the larger the size of waves that can reach the shore becomes. Waves will eventually break when the depth is shallow enough and runup on or over land. When analyzing wave hazards along beaches, an eroded beach condition should be evaluated as this often results in the most hazardous conditions. Furthermore, large waves also occur during large coastal storms which tend to occur most frequently in winter months, when beaches are typically at their narrowest.

There are multiple ways to evaluate coastal flooding that consider sea level rise with ranging levels of complexity as well as data, effort, and skill required. Another important factor when analyzing flooding is the resolution and accuracy of available topographic data. Small changes in topography can result in vastly different results.

Certain low-lying coastal areas may not be exposed to either swell or significant wind waves and, in these areas, coastal flooding is likely dominated by extremely high ocean water levels that can occur during a combination of high tides, atmospheric influences like storm surge, and oceanographic influences like El Niño. This section will generally progress through methods for evaluating coastal flooding where increasing attention is given to the influence of wave hazards starting with a discussion on "bathtub" approaches and moving to site specific wave hazard analyses.

"Bathtub" Approach

One of the simplest approaches to analyzing flood risk is to compare ground elevations to current or future flood levels. A "bathtub" approach, as it's commonly called, takes a flood elevation, e.g., 10 ft above mean sea level, and then assumes all elevations in the area of interest below that flood elevation will be flooded. This approach can easily consider sea level rise by simply increasing the flood elevation by the amount of sea level rise being analyzed e.g., 10 ft + 1 ft of sea level rise = 11 ft. The most important factors for this kind of analysis are determining the appropriate flood elevations and finding appropriate topographic data.

Bathtub approaches are extremely simplistic, which makes them very easy to implement. However, they may not be appropriate in some cases. Bathtub approaches can make sense for areas where flooding is expected to increase linearly with sea level rise; this is often the case for low-lying areas along partially enclosed bays or inlets that experience flooding as result of extreme still water levels and where significant erosion and shoreline change is not expected. It is not appropriate for areas where water is expected to be dynamic such as areas exposed to large waves or fast-moving flow down rivers or creeks. Bathtub approaches to projecting future flooding also rely on estimates for existing floodwater elevations which could come from previous studies such as FEMA studies or estimates of extreme coastal water levels for NOAA tide stations.

Hydrodynamic Models

Another approach for evaluating coastal flood risk is through the development or use of hydrodynamic models. Hydrodynamic models simulate the water levels and currents that occur during storm conditions and can take considerable effort to develop, calibrate, and validate. Hydrodynamic models can also simulate waves, including wave runup and overtopping, in great detail. Generally, it only makes sense to develop site-specific hydrodynamic models for a larger areas on the order of miles since the models need to consider appropriate boundaries that capture relevant features, such as the entirety of a coastal lagoon, to avoid undue modeling errors. To consider sea level rise, hydrodynamic models are essentially re-run with the sea level rise incorporated in the input conditions.

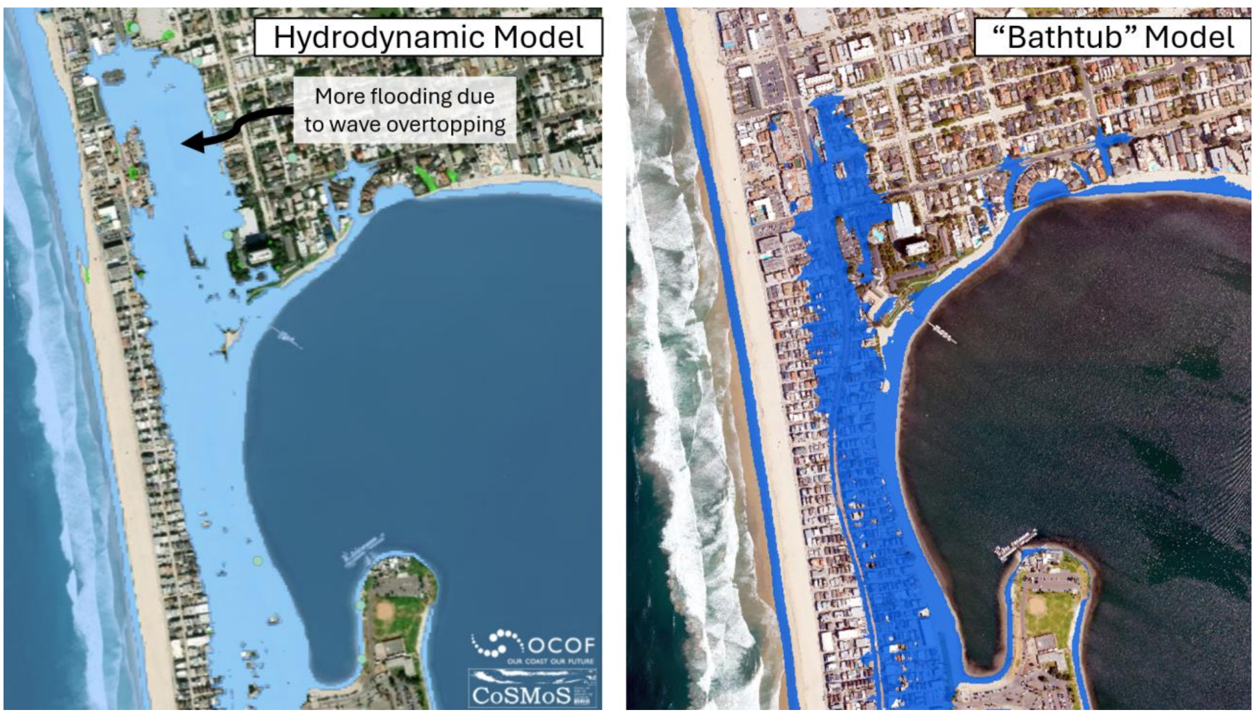

Figure B-4. Illustration of differences between a hydrodynamic model (CoSMoS; 100-year flooding 0 ft SLR) and a "bathtub" model (all areas below 8 feet, NAVD88 shaded blue)

The USGS has developed flood models and published hydrodynamic flood modeling results statewide for increments of sea level rise ranging from 0.25 meters to 5 meters, providing a useful tool for evaluating both existing coastal flood risk and future flood risk as worsened by sea level rise. Importantly, CoSMoS models were developed on large scales and, while a great tool for screening and high-level planning analysis, require sound technical judgement when interpreting results for uses that might require higher levels of detail. When evaluating the results from any model, it is generally good practice to examine the results for similar conditions from separate models or, if possible, validate with observations (e.g., flooded areas) for real events with similar storm conditions. When a higher degree of confidence and resolution might be desired such as for evaluating the potential performance of a proposed tide gate or pump system, developing a site-specific model would provide results more appropriate for use in design.

FEMA Flood Zones

FEMA develops and maps flood zones including for areas subject to coastal flooding from both waves and extreme static water levels. These flood zones do not consider future sea level rise and generally represent areas that could be impacted by flooding from events with a 1% probability of occurring in a year. In coastal areas, “VE” Zones generally represent areas of high wave hazards, while “A” and “AE” Zones generally represent areas of moderate to minimal wave hazards. Zones VE and AE will specify a base flood elevation (BFE) which is meant to represent the elevation of the 1% annual exceedance probability total water level. Total water level combines all contributions to the water level at a given time, including mean sea level, tides, seasonal and storm effects, wave runup and other factors (**Fig.** B-5).

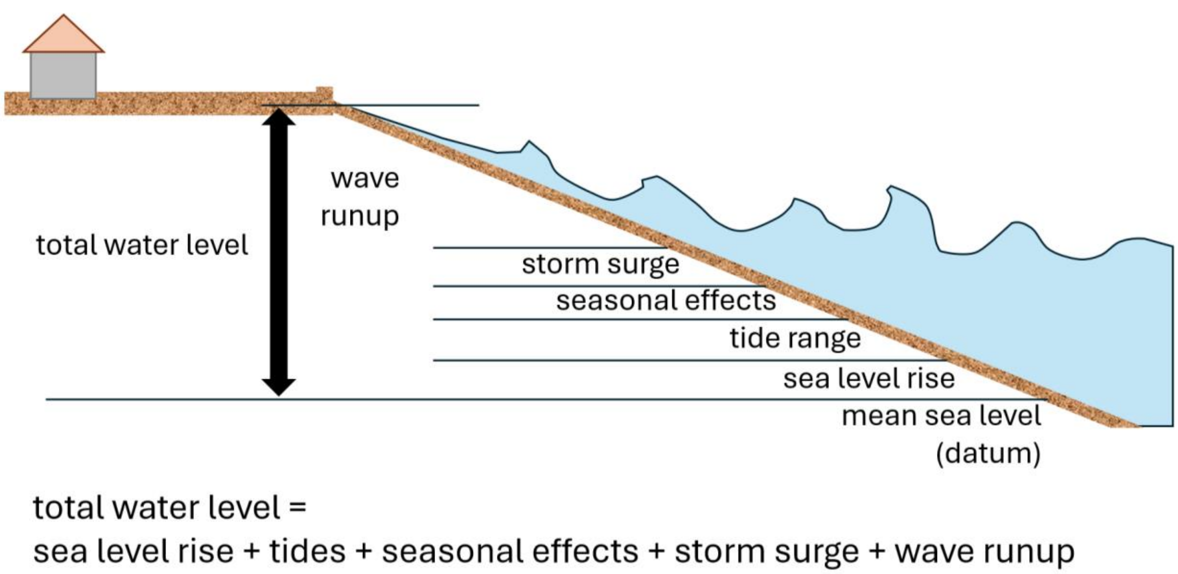

Figure B-5. Illustration of components of coastal total water levels (adapted and simplified figure 1 of Barnard *et al.*, 2019)

There are several relatively simple analytical approaches that relate current FEMA flood zones to future coastal conditions considering sea level rise. These approaches often don’t require the level of data and effort as developing new hydrodynamic models and can provide reasonable, rough estimates for future flood risk that leverage the detailed studies conducted by FEMA. One example of this kind of an approach is detailed in a Technical Methods Manual by Battalio *et al*., 2016 and involves determining the portion of the total water level (or Base Flood

Elevation) due to wave runup, increasing the wave runup based on a "morphology function" determined by the erodibility of the backshore, and calculating a new total water level by adding both sea level rise and the increase in wave runup. This method is relatively simple when the information on the wave runup estimates used to determine the FEMA total water levels is available and accounts for the compounding effects of sea level rise on total water levels illustrated in Figure B-6 below. Translating current FEMA flood zones to future coastal conditions may make sense for jurisdictions looking to create hazard maps that consider sea level rise but are also familiar in form to existing flood zones, which may aid with the application of existing flood ordinances.

Site Specific Wave Hazard Analyses

In some cases, site-specific wave hazards analyses that consider the effects of sea level rise may be needed to adequately assess risks to new development along the coastline. This often requires consideration of the potential wave runup elevations that consider higher static water levels, sea level rise induced beach change, and expected 100-year storm conditions. There is a diversity of methods for estimating wave runup and overtopping. Because of the dynamic nature of extreme wave events, empirical equations can be an important tool for simplifying analyses while maintaining appropriate consideration of engineering uncertainty. These empirical equations typically relate inputs such as wave conditions (wave height and period), beach slope, a structure's (such as a revetment's or seawall's) roughness, and a structure's slope.

In general, hazards analyses should consider risk from extreme conditions (often the 1% annual exceedance probability or "100-year" event). Because coastal flood events typically involve a combination of several partially related factors such as storm surge, wave conditions, and acute erosion, it can be challenging to determine exact probabilities. To address this complexity, deterministic approaches attempt to estimate the conditions of a 100-year event, generally assuming reasonable conservative estimates for things like wave height, period, and event-based beach erosion often through professional experience or judgment. Other more probabilistic approaches leverage existing datasets for things like observed water levels and wave conditions to create a hindcast of wave runup elevations that can inform a statistical analysis to estimate a range of extreme events.

Notably, while the field of coastal engineering has developed a range of methods for predicting wave hazards across the globe, different methods have been shown to be more or less appropriate for California's (and the Pacific North American coast more broadly) oceanographic context. In California, much of coastal wave hazard is influenced by the large swell which creates large fluctuations in water levels at the shore through what are called infragravity waves. This dynamic setup, as it is also called, can create deeper waters long enough for larger waves to break closer to shore where there is less space for their energy to be dissipated. This dynamic is notably different than the Gulf and Atlantic coasts where extreme wave hazard is typically dominated by large storm surge from strong storm systems like hurricanes. FEMA, as part of its update for coastal hazard mapping on California's open coast, developed guidelines to this end that can be found here.[125]

Proper consideration should be given to selecting an appropriate method for estimating wave hazards including how sea level rise will be included in the inputs used for such an analysis. Most notably, sea level rise will increase static water elevations which not only increases the baseline from which wave runup is calculated but also increases the size of waves able to reach the shore. Similarly, where wave hazards are being analyzed on coastal structures, sea level rise induced beach retreat should be considered such that the depth of water at the toe of structures will increase. In shorelines where the backshore is armored or otherwise resistant to erosion, this leads to a compounding effect from sea level rise where one foot of sea level rise could lead to a two to four foot increase in total water level (Battalio *et al.*, 2016). These compounding effects are illustrated below (**Fig.** B-6).

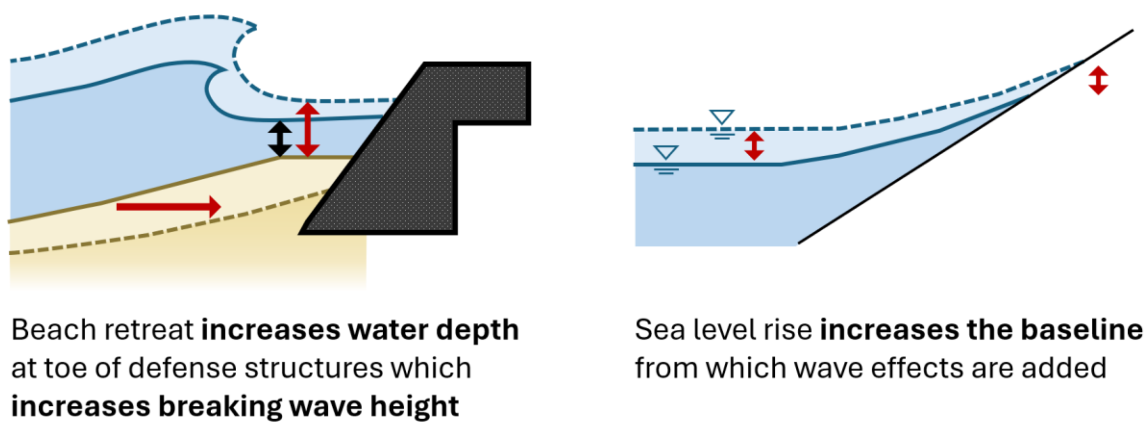

Figure B-6. Diagram illustrating the compounding effects of sea level rise on coastal wave hazards (Source: J. Smith, 2024)

Summary

In summary, coastal flooding events can be influenced by a variety of factors but in simple terms can be grouped in two categories: flooding strongly influenced by waves and coastal flooding not-strongly influenced by waves. While there is a variety of approaches to estimating future coastal flood risk as worsened by sea level rise, selecting the appropriate approach should be based on the levels of uncertainty and precaution desired by the relevant decision makers.

[125] Note that while the document linked here has been superseded by the FEMA Policy for Flood Risk Analysis and Mapping, the document contains useful guidance to support implementation of the new standards

FLUVIAL/RIVERINE FLOODING

Where rivers, creeks, and drainage channels meet the ocean, high water levels can "back up" upstream. Sea level rise will increase water levels at the downstream end of watersheds and so can increase fluvial flood risk even on days when coastal flooding may not be a concern (**Fig.** B-7). Most fluvial flood risk in the State has been assessed as part of FEMA flood insurance rate maps which generally map flood zones for the 100-year recurrence interval or 1% annual exceedance probability event, which reflect historical observations and do not capture the effects of future sea level rise. These zones have been developed over decades from a multitude of FEMA-commissioned studies.

Fluvial flood risk is generally reassessed when there are proposed changes to topography within or near floodplains, when bridges are being constructed, retrofitted, or replaced, and as part of flood control improvement projects. Generally, fluvial flood risk is assessed through the use of hydraulic models of varying levels of complexity.

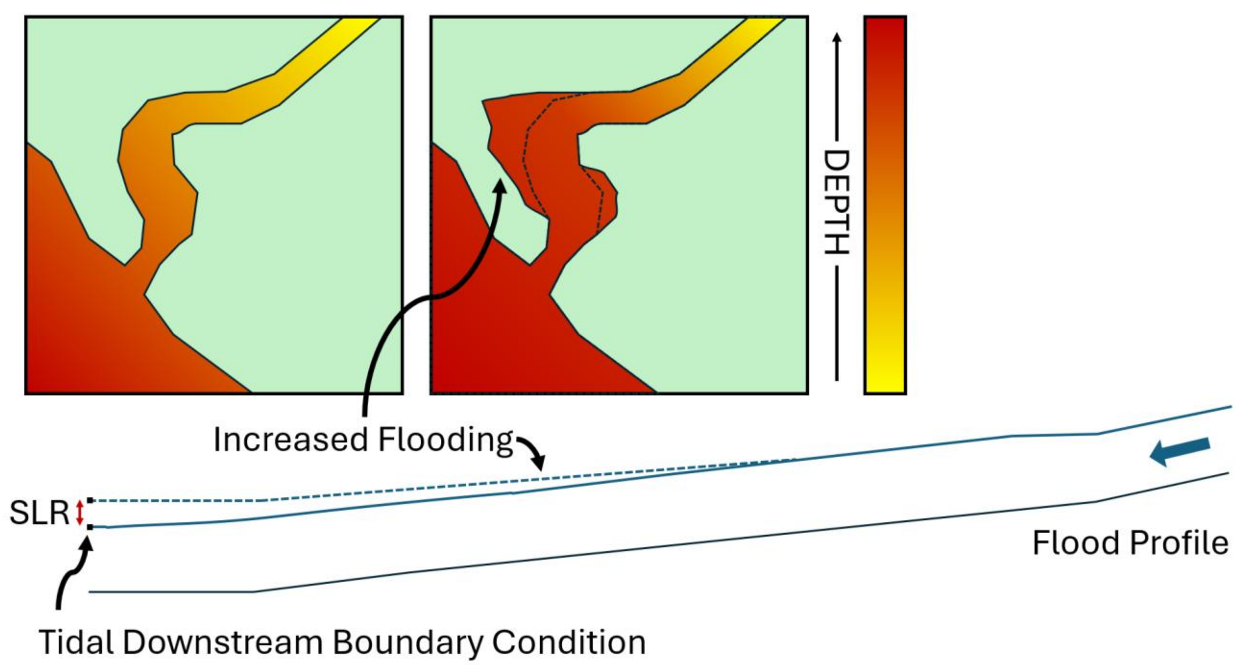

Figure B-7. Diagram illustrating how sea level rise can influence fluvial flooding upstream (Source: J. Smith, 2024).

The inland geographic extent of where sea level rise is expected to affect fluvial flooding levels varies. Generally, channels with flatter slopes will see a greater extent where higher sea levels affect fluvial flood levels. Channels where flow is constricted due to a narrowing in the channel or a flow control structure will generally not see effects from higher sea levels upstream of those constricted areas because the flow is controlled by that constriction rather than downstream water levels.

To evaluate the effects of sea level rise on fluvial flood risk, hydraulic models should use conservative downstream boundary conditions increased with the amount of sea level rise being analyzed.

For most situations, the 100-year event should be used as the design event for hazards like coastal or fluvial flooding. The term “100-year” is equivalent to saying a storm or flow event has a 1% annual probability of exceedance. There is a 22% probability that a 100-year storm event or greater will occur during a 25-year period and over 53% probability that a 100-year storm or greater will occur at least once during a 75-year period. Even so, the 100-year 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.

PLUVIAL/STORMWATER FLOODING

Pluvial flooding (also called “urban” flooding) is flooding that occurs as a result of runoff from rainstorms. While pluvial flooding can happen in natural watersheds its often most severe in altered watersheds. Examples include ponding in depressions, along the edges of topographic barriers, or around constrained stormwater infrastructure. Ponding can occur in depressions when runoff exceeds the capacity of stormwater infrastructure like drains or pumps such as underpasses (see an example in **Fig.** B-8 below). Any areas where stormwater is controlled and drained to coastal waters could potentially see worsened flooding as a result of sea level rise. This is because stormwater drainage capacity can be reduced by higher coastal water levels (including as increased by sea level rise) causing a “backing up” of stormwater drainage systems.

It can be difficult to initially identify areas where stormwater drainage systems could be significantly impacted by higher sea levels. Generally, the areas with the greatest potential vulnerability are areas that are close to or below the elevation of daily highest tides (mean higher high water). Some drainage systems already require special infrastructure for their drainage to coastal areas, such as drainage systems that rely on pumps or tide gates. These areas are an example where the effects of sea level rise on the function of the stormwater systems should be assessed.

Stormwater systems are often evaluated through hydrology and hydraulics (or H+H) modeling which can have varying levels of complexity but which ultimately simplifies drainage systems as a network of drainage infrastructure (stormwater pipes, inlets, pumps, etc.) and drainage areas (e.g., small watersheds) which, with rainfall estimates and information about the drainage area such as the slopes, surface types, etc., are used to determine the flow of water into the drainage system.

Sea level rise can be considered in these modeling efforts by increasing downstream water level conditions, altering pump capacities by evaluating the effects of higher water levels on pump curves, and increasing assumed baseloads to the drainage system from increased groundwater inputs from groundwater rise.

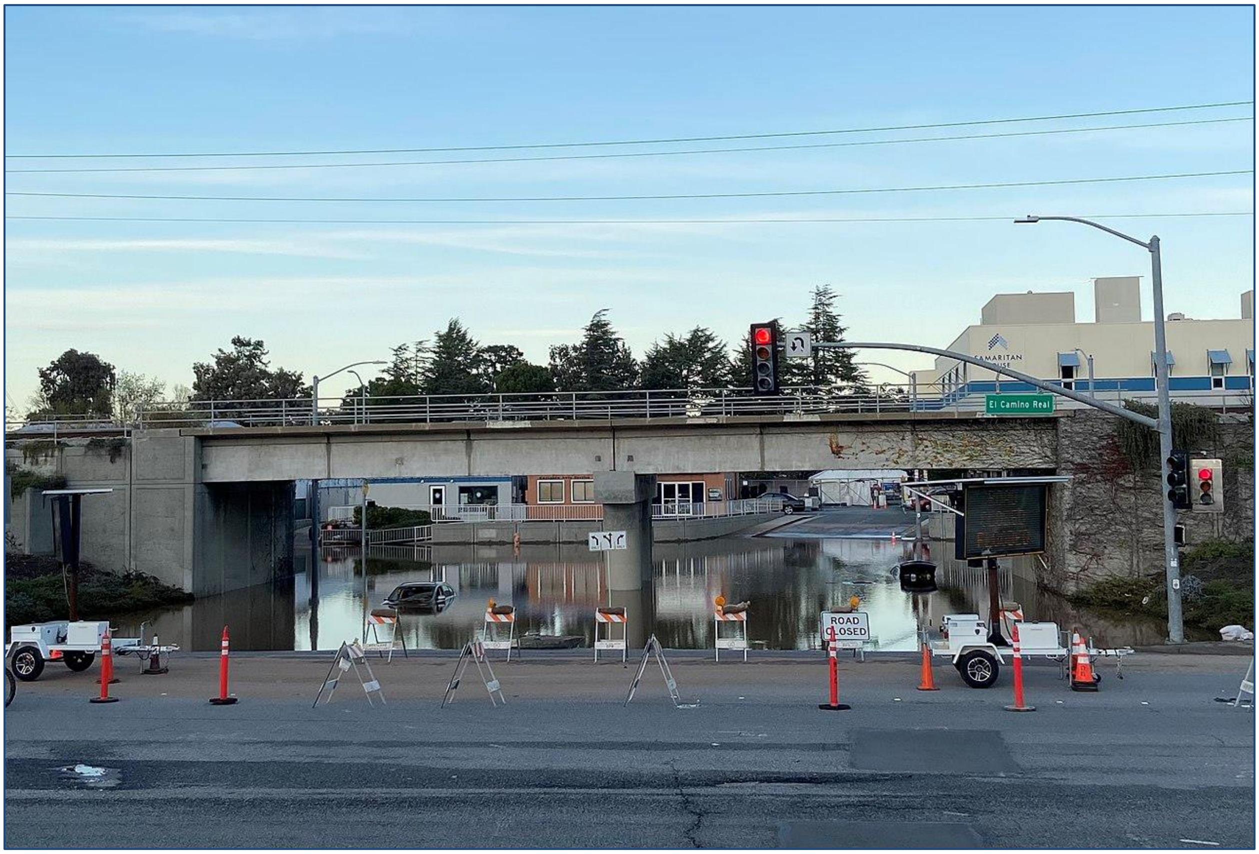

Figure B-8. Photo of pluvial flooding at an undercrossing in San Mateo, CA (Source: B. Washburn, www.flicker.com/btwashburn; CCA 2.0)

GROUNDWATER RISE

Where surficial groundwater is hydraulically connected to the ocean, sea level rise can cause an increase in groundwater tables (decreasing depths from surface to groundwater), increased salinity of groundwater, and/or increased groundwater flow (Rotzoll & Fletcher, 2013).

Higher groundwater elevations can cause a variety of problems ranging from increased liquefaction risk, damage to roads and buried structures (e.g., basements, pipes, and utilities), decreased capacity for infiltration of rainfall, mobilization of contaminants in soil, and in some cases, temporary or permanent emergence of groundwater onto the surface (Hill *et al.*, 2023).

Saline intrusion into groundwater used for irrigation or potable water uses can be a major issue where such groundwater is the only or a major source of fresh water. When saline ocean water interacts with fresh water in the ground, it typically forms what is referred to as a saline groundwater wedge with boundary between fresh and saline groundwater decreasing in elevation with distance away from coastal waterbodies. This wedge is expected to move inland with sea level rise (Glover, 1959) which will increase the geographic extent of saline intrusion into shallow groundwater wells landward. This concept is illustrated in Figure B-9 below.

In some areas, groundwater infiltrates buried stormwater or wastewater pipes which can both influence groundwater elevations around them. The leaking of groundwater into pipes can increase “baseloads” at stormwater or wastewater treatment facilities, limiting capacity and increasing operating costs (May *et al.,* 2022).

Changes to groundwater as a result of sea level rise can be modeled but are often limited in the availability of critical information such as existing or historic groundwater levels and local geology, which are needed for calibration and validation. There are several approaches where groundwater change could be considered in analyses using more conceptual or qualitative approaches as well.

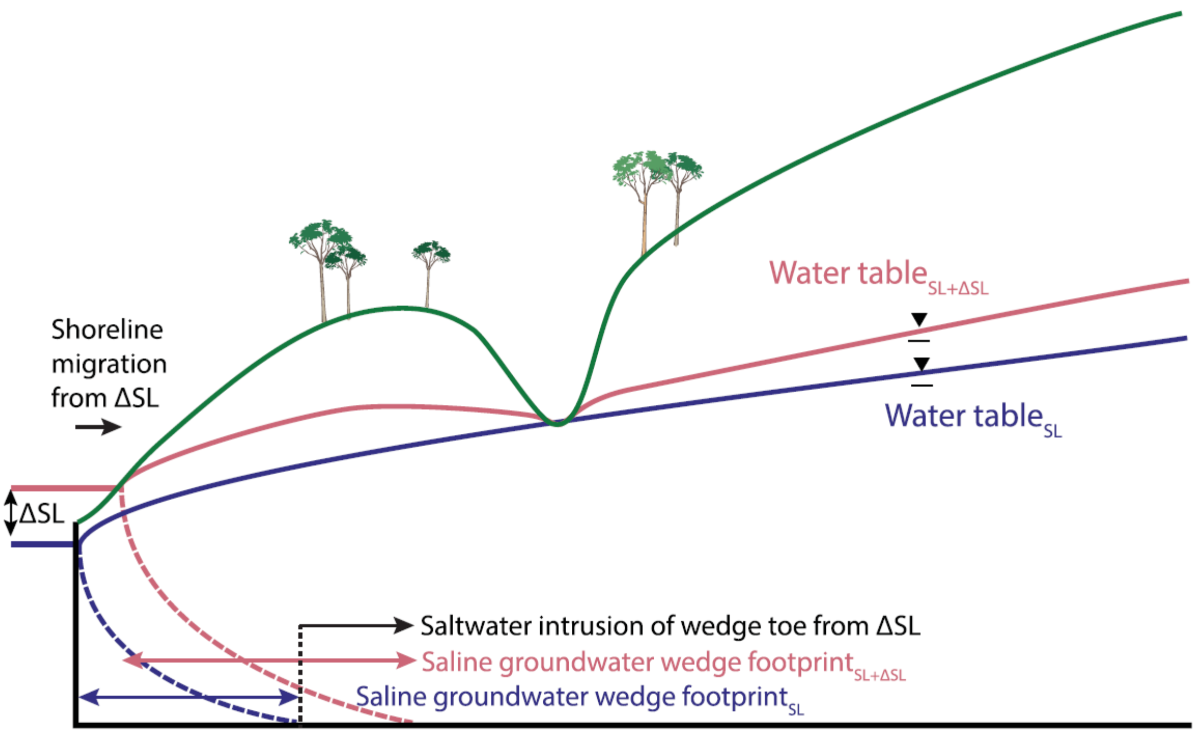

Figure B-9. Diagram from Befus *et al.* 2020 illustrating current groundwater table and saline groundwater wedge in blue and future groundwater table and saline groundwater wedge in pink. Note groundwater table is limited controlled by local topography in this example.

As part of CoSMoS, USGS partnered with groundwater modeling experts to create a statewide dataset of modeled equilibrium groundwater depths for both present sea level and increments of sea level rise (Befus *et al*., 2020, **Fig.** B-9). The modeled equilibrium groundwater surface represents the long-term average elevation of groundwater flowing along the coast for the tidal datums considered (local mean sea level and mean high water) and can be viewed as a baseline that seasonal, tidal or shorter-term influences such as storms would start from. The model results are largely a function of topography, distance from coastal water bodies, and how readily water moves through the ground (via pore spaces, fracture networks, etc.), a property known as hydraulic conductivity. The USGS model produced projections for three different hydraulic conductivity values ranging across three orders of magnitude due to a lack of detailed information on hydraulic conductivity at both fine scales and available statewide. These three hydraulic conductivity results help demonstrate the range in uncertainty, and users can focus on the dataset associated with the hydraulic connectivity value they know to be representative of their local geology. While the CoSMoS-GW results are helpful for high level analyses and screening for where groundwater rise may be an issue in local hazard planning, site-specific groundwater models developed with higher resolution topographic and geologic data would provide results appropriate for use in planning stormwater and flood control systems, or in designing individual projects.

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).

Figure B-10. Screenshot of ASCE Tsunami Hazard Tool showing results for the Venice-Marina del Rey area for the 2,475-year probabilistic tsunami hazard analysis

Recent advancements by the California Geological Survey (CGS) have significantly improved the availability of high quality tsunami data statewide for use in hazard analyses and planning. These data including the maps of California Tsunami Hazard Area (which was created for use in disaster preparedness and evacuation planning) are available on the CGS website. Several third party websites are also available as tools or viewers to access products that utilize the statewide probabilistic tsunami hazard analysis results such as the American Society of Civil Engineers (ASCE) Tsunami Design Geodatabase which is used to determine tsunami loads for critical facilities as part of the building code (Fig. B-10). There are currently no statewide datasets for tsunami inundation areas that consider sea level rise, though these are in progress. A rough estimate of how to adjust existing available tsunami inundation data to consider sea level rise is by assuming a 1:1 increase in tsunami flow depths with sea level rise i.e., if any area is shown to have a 4 ft tsunami flow depth, with 1 ft of sea level rise, it could have 5 ft of tsunami flow depth.

SUMMARY

Sea level rise will worsen many of today's hazards. Incorporating the effects of sea level rise into estimates of hazard conditions is not always simple. This appendix can serve as a resource that outlines the variety of ways sea level rise can be considered for different hazards as well as some of the tradeoffs in difficulty or level of detail that come from the diversity of methods.

As this appendix has outlined, sea level rise will be a persistent increase to baseline sea levels from which a variety of more dynamic factors such as storm surge and coastal wave storms will be increase, sometimes non-linearly with each foot of additional sea level rise. The approximate magnitudes and timescales of these factors are outlined in Table B-1 below.

When developing local hazard conditions for use in coastal planning and analyzing coastal development, there is a wide array of available tools, some of which have already been mentioned, available to aid in analysis of future hazards. These range from viewers of detailed modeling efforts to technical datasets and guidance that will aid in the development of localized or site-specific hazard analyses. These tools and resources are outlined in Table B-2 below.

Table B-1. 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. F)	0.5 – 1.3	0.15 – 0.4	Ongoing	Persistent
OPC Sea Level Projections 2000 – 2100 (SF tide gauge; see also App. F)	1.0 – 6.5	0.3 – 2.0	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.

Table B-2. General Resources for Developing Local Hazard Conditions

Resource	Description	Link
California Coastal Records Project	Oblique photograph time series; useful for general information on shore type, trends in beach or bluff retreat.	www.californiacoastline.org
UCSB FrameFinder	Historic aerial imagery spanning 20th and 21st centuries.	https://mil.library.ucsb.edu/ap_indexes/FrameFinder/
U.S. Coast Survey Maps "T-Sheets" (Southern California)	Historic surveys from mid-19th century; detail geomorphic and shoreline features; have been adapted to identify historic habitats.	https://www.caltsheets.org/socal/index.html https://scwrp.databasin.org/maps/new/#datasets=159884c34c9848949d76ef1f72d468b4

NOAA Data Access Viewer	Land cover, elevation (LiDAR datasets and digital elevation models), aerial imagery (including pre- and post-storm events).	https://coast.noaa.gov/dataviewer/#/
Regional Sediment Management Studies	Range of studies covering oceanographic conditions, beach and bluff change data, flooding and wave impacts, and historic conditions.	https://dbw.parks.ca.gov/?page_id=29239
CoastSat	Viewer to explore global shoreline change trends and information on the open-source CoastSat tool for extracting shoreline data from satellite imagery.	http://coastsat.wrl.unsw.edu.au/
USGS Coastal Change Hazards Portal	Viewer to explore a range of USGS datasets on extreme storms, shoreline change, historical shoreline positions.	https://marine.usgs.gov/coastalchangehazardsportal/
California Coastal Cliff Erosion Viewer	Viewer to explore cliff erosion rates observed from 1998 to 2011 and 2009 to 2016.	https://siocpg.ucsd.edu/data-products/ca-cliff-viewer/
Coastal Storm Modeling System (CoSMoS)	Detailed predictions of storm-induced coastal flooding, erosion, and groundwater rise over large geographic scales.	https://www.usgs.gov/centers/pcmsc/science/coastal-storm-modeling-system-cosmos#overview
Our Coast Our Future (OCOF)	Viewer with hazard map to explore range of data from USGS CoSMoS.	https://ourcoastourfuture.org/
FEMA California Coastal Analysis and Mapping Project | Open Pacific Coast Study	Statewide effort commissioned by FEMA to update open Pacific Coast coastal hazard maps for Flood Rate Insurance Maps. Intermediate Data Submittals include range of wave hazards information.	Not easily available online. Reports and studies conducted at the county level and may be available from county hazard offices or FEMA Region 9 https://www.fema.gov/locations/contact/california
Coastal Data Information Program (CDIP)	Current and historical information on wind, waves, and water temperature, wave and swell models and forecasting. Localized nearshore wave data available at "MOP" lines.	https://cdip.ucsd.edu/ https://cdip.ucsd.edu/mops/
FEMA National Flood Hazard Layer	Viewer includes Flood Rate Insurance Maps (FIRMs). Note that FIRMs do not consider sea level rise or other effects of climate change.	https://www.fema.gov/flood-maps/national-flood-hazard-layer
USACE Wave Information Study (WIS)	National resource with long-term wave climate and multi-decade hindcasts of wave conditions.	https://wis.erdc.dren.mil/

FEMA Guidelines for Flood Risk Analysis and Mapping Activities	Extensive range of guidance and standards including focused guidance on coastal wave hazard analysis.	https://www.fema.gov/flood-maps/guidance-reports/guidelines-standards
NOAA Sea Level Rise and Coastal Flooding Impacts Viewer	"Bathtub" model showing areas below mean higher high water with a range of 1-foot increments of sea level rise.	https://coast.noaa.gov/slr/
Cal-Adapt Climate Tools	Range of tools and datasets for considering the effects of climate change including sea level rise and projected changes in intensity and frequency of extreme precipitation events.	https://cal-adapt.org/tools/
California Geological Survey Tsunami Page	Includes information on tsunami hazards, preparedness and evacuation resources, and data and reports for statewide probabilistic tsunami hazard analysis.	https://www.conservation.ca.gov/cgs/tsunami
ASCE Tsunami Design Geodatabase	Mapped runup extents and runup elevations used in ASCE 7 Standards.	https://asce7tsunami.online/

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