DOCKETED

Docket Number:	15-AFC-01
Project Title:	Puente Power Project
TN #:	215540
Document Title:	Exhibit - Vandever et al (Coastal Disasters 2015)
Description:	N/A
Filer:	PATRICIA LARKIN
Organization:	SHUTE, MIHALY & WEINBERGER LLP
Submitter Role:	Intervenor Representative
Submission Date:	1/24/2017 2:19:39 PM
Docketed Date:	1/24/2017

Conceptual response of runup-dominated coastlines to sea level rise and anthropogenic adaptation measures

J. Vandever, PE, M.ASCE[1], J. Mull, PE, M.ASCE[2], D. Hatheway, CFM[3], V. Geronimo, PE, CFM, M.ASCE[4], and K. May, PhD, PE, M.ASCE[5]

[1]Coastal Engineer, AECOM, 1333 Broadway, Suite 800, Oakland, CA 94612; PH (510) 874-3084; email: justin.vandever@aecom.com
[2]Coastal Engineer, AECOM, 1501 4th Avenue, Suite 1400, Seattle, WA 98101; PH (206) 438-2318; email: jeremy.mull@aecom.com
[3]Senior Coastal Scientist, AECOM, 401 West A Street, Suite 1200, San Diego, CA 92101; PH (619) 905-9488; email: darryl.hatheway@aecom.com
[4]Senior Project Manager, AECOM, 1333 Broadway, Suite 800, Oakland, CA 94612; PH (510) 874-3210; email: vince.geronimo@aecom.com
[5]Climate Adaptation Practice Leader, AECOM, 1333 Broadway, Suite 800, Oakland, CA 94612; PH (510) 874-3274; email: kris.may@aecom.com

ABSTRACT

There is considerable interest in understanding the hydrodynamic and geomorphic response of coastlines to sea level rise (SLR). Various researchers have investigated the nature of these changes in storm surge-dominated environments; however, fewer studies have investigated the response of wave runup-dominated coastlines. This paper develops a conceptual model of total water level (TWL) response to SLR and shoreline change for a variety of shoretypes. The conceptual model was developed through analytical techniques and application of a 1-D transect-based TWL analysis, taking into account the effects of SLR and shoreline change. The results indicate that dynamic shoretypes such as sandy beaches, dunes, and erodible bluffs may experience a linear increase in TWL in response to SLR and shoreline change, while static shoretypes such as resistant rocky cliffs and coastal structures may exhibit a non-linear increase in TWL. The study findings can be used to communicate the implications of implementing various physical adaptation strategies to reduce exposure to coastal hazards and to inform better decision making in the face of changing coastal conditions due to climate change.

INTRODUCTION

Coastal scientists, managers, and engineers face an unprecedented challenge to plan for the impacts of sea level rise (SLR) along our coastlines. While scientists have high certainty that sea levels have risen historically and will continue to rise at an accelerated rate over the remainder of this century, it is difficult to predict how much SLR will occur at a given location over a given time frame. Developing accurate regional and local SLR projections poses additional challenges to local communities because the rate of SLR is not uniform everywhere.

The degree of uncertainty is even greater when predicting the hydrodynamic and geomorphic response of shorelines to SLR. Anthropogenic responses to future coastal hazards and ongoing changes in land use and development, which may further affect the hydrodynamic and geomorphic processes, are also unknown. Despite these uncertainties, coastal communities must make coastal planning decisions today based on limited information and high uncertainty. Part of that planning effort involves developing an understanding of the landward extent of coastal hazard zones and how they will change in the future.

Coastal planners need tools to conceptualize these complex processes and understand how shorelines will respond to future SLR, including changes in wave runup and shoreline change. California state guidance (California Coastal Commission 2015) requires communities to evaluate the impacts of SLR and shoreline change when permitting coastal development and making land use decisions. Federal, state, and local agencies have recently completed or are conducting ongoing work to inform planning efforts, including the Our Coast Our Future project, NOAA's Sea Level Rise and Coastal Flooding Impacts Viewer, the Pacific Institute's Impacts of Sea Level Rise on the California Coast (Pacific Institute 2009; Revell et al. 2011), and Climate Central's Program on Sea Level Rise. These products consist primarily of online data viewers or geospatial layers which provide a good starting point for assessing the exposure component of SLR vulnerability; however, there is no widely available guidance or rule-of-thumb to easily estimate the increase in future conditions wave runup elevations.

The purpose of this paper is to develop a conceptual model of total water level (TWL = tide + storm surge + wave setup + wave runup) response to SLR and shoreline change for a variety of shoretypes (e.g., erodible bluffs, resistant rocky cliffs, sandy beaches, dunes, and coastal structures). The conceptual model was developed through analytical techniques and application of a 1-D transect-based TWL analysis, taking into account the effects of SLR and shoreline change to evaluate future changes in wave runup along the California coast. The study findings can be used to communicate to coastal planners the implications of implementing various physical adaptation strategies to reduce exposure to coastal hazards and to inform better decision making in the face of changing coastal conditions due to climate change.

BACKGROUND

Effect of SLR on Coastal Hazards

There is considerable interest in understanding the hydrodynamic and geomorphic response of coastlines to SLR. Various researchers have investigated the nature of these changes in storm surge-dominated environments, although fewer have focused on wave runup-dominated environments. Climate change and SLR may affect future coastal flood hazards in a variety of ways, including changes to storm surge, tidal hydrodynamics, overland wave propagation, offshore waves, and wave runup.

A summary of prior studies which investigated the effect of SLR on coastal flood hazards is provided below. The response of storm surge, tidal hydrodynamics, and wave runup to SLR has been examined across a variety of coastal environments, including Puerto Rico (RAMPP 2010), the Gulf Coast of the United States (Atkinson et al. 2013; Bilskie et al. 2014; Mousavi et al. 2011; Smith et al. 2010), Pacific coral atolls (Quataert et al. 2015; Storlazzi et al. 2015), estuarine Bangladesh (Pethick and Orford), the North Sea (Arns et al. 2015), and San Francisco Bay (AECOM et al. 2011; Knowles 2010; Holleman and Stacey 2014), and elsewhere. These studies have applied complex coupled storm surge and wave numerical models, physical models, and analytical techniques to estimate the future changes in storm surge and wave height in response to SLR. Coastal storm surge and wave dynamics are exceedingly complex and there is no one-size-fits-all approach or universal result which can be easily applied to all coastal settings, so site-specific evaluations have thus far been necessary (Atkinson et al. 2013).

Review of these studies revealed that some locations may experience what is referred to as a "non-linear" increase in storm surge or wave runup in response to future SLR. A "linear" response means that the increase in storm surge or wave runup is equal to the amount of SLR (a 1:1 relationship) and a non-linear response means that the future conditions storm surge or runup increases by an amount greater than SLR.

Effect of SLR on Wave Runup

While storm surge magnitude and tidal hydrodynamics have been shown to increase non-linearly in response to SLR in some locations, fewer studies have investigated the hydrodynamic response of wave runup-dominated shorelines to SLR. Kanoglu and Synolakis (1998) investigated wave runup processes using analytical and laboratory methods for a beach backed by a seawall and observed a dramatic increase in wave runup as water depth increased and the breaker location moved closer to the seawall. Chen and Alani (2012) and Chen (2015) analyzed the reliability of sea defenses in response to SLR and also noted the effect of SLR in increasing the local wave height at the structure toe, leading to enhanced wave runup and greater probability of structure failure. The authors proposed that increases to coastal structure crest elevations in the future may need to be double the amount of SLR to maintain existing levels of flood protection. Similar enhancement of wave runup and coastal flooding has been observed along low-lying coral atolls, where depth-limited wave breaking is controlled by shallow reefs, such that SLR allows larger waves to propagate landward and break on the shoreline (Storlazzi et al. 2015). These findings suggest that the concept of linear vs. non-linear response to SLR can be applied to wave runup-dominated shorelines, where a non-linear response indicates a future condition where the increase in wave runup exceeds the amount of SLR.

California Coastal Flood Processes

The findings presented in this paper are derived from analyses conducted along the California coastline, which is assumed to be representative of other wave runup-dominated environments. The California coastline experiences mixed semidiurnal tides, with two high and two low tides of unequal height each day. In addition, the tides exhibit strong spring-neap variability with the highest monthly tides occurring during summer and winter months. High tides typically range between six to eight feet and storm surge is relatively small (1 to 2 feet) compared to tropical cyclone-generated storm surge. Winter storms are typically characterized by significant wave heights of 10 to 30 feet and peak periods of 14-18 seconds.

A key parameter used to evaluate the extent of coastal flooding in wave runup-dominated environments is the total water level. The TWL comprises the astronomical tide (or stillwater level), wave setup, and wave runup. TWL is the vertical elevation reached by wave runup processes at the shoreline (Figure 1). The Federal Emergency Management Agency's (FEMA) Base Flood Elevation (BFE) is derived from the 1-percent-annual-chance TWL, which serves as a useful benchmark for evaluating future TWL changes in response to SLR.

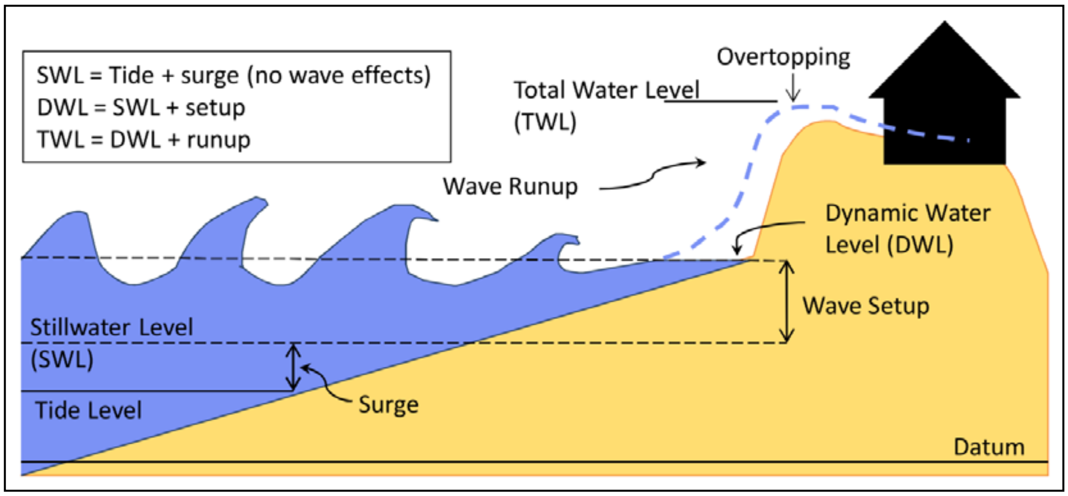

Figure 1. Definition Sketch of Total Water Level (TWL)

Regional Sea Level Rise Projections

Observations of sea levels at tide stations indicate a long-term historical global SLR rate of approximately +1.7 mm/yr over the 20th century (Intergovernmental Panel on Climate Change (IPCC) 2013; Parris et al. 2012). Recent satellite altimetry data suggest an increase in the rate of global SLR to approximately +3.2 mm/yr from 1993-2012. IPCC (2013) estimated that it is very likely that 21st century rates of global SLR will exceed recent observed rates under all possible future greenhouse gas emissions scenarios. Spatial variability in surface wind patterns, ocean currents, vertical land motion (subsidence or uplift), seawater temperature and salinity, and gravitational effects contribute to regional and local variations in future SLR projections relative to global projections (IPCC 2013).

The 2012 National Research Council (NRC) Report *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* is recommended by the California Coastal Commission (2015) as the best available SLR science for the state of California. Table 1 presents the NRC SLR projections for San Francisco. A 12-inch and 36-inch NRC mid-range projection and 24-inch and 66-inch high-range projections were selected for use in this study for 2050 and 2100. Quadratic curve fits were developed for the mid-range and high-range SLR scenarios and will be used in subsequent analyses (Figure 2).

Table 1. SLR Estimates for San Francisco Relative to the Year 2000

Year	*Projection (inches)*	*Range (inches)*
2030	6 ± 2	2 to 12
2050	11* ± 4	5 to 24
2100	36 ± 10	17 to 66

Source: NRC (2012). Notes: *As a simplifying assumption, the 2050 mid-range value selected for this study is 12 inches rather than the 11 inch value noted in the table.

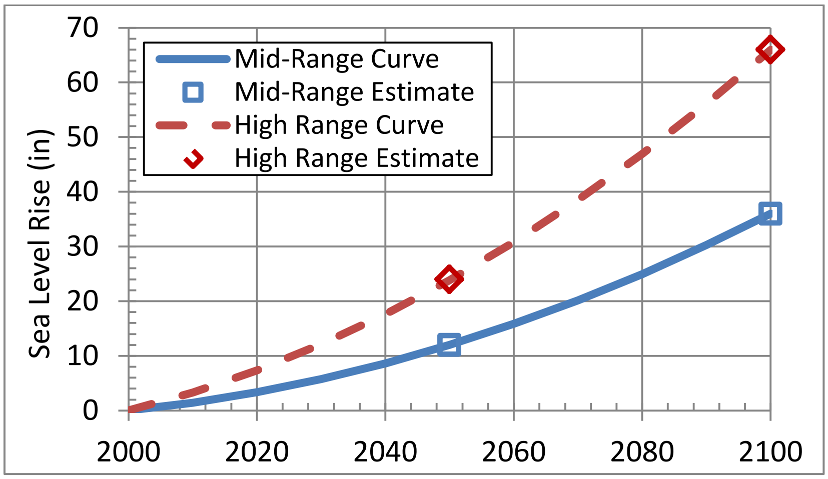

Figure 2. SLR Curves for NRC Mid-range and High-range Scenarios

METHODOLOGY

The overall purpose of the this analysis is to examine the TWL response to SLR and shoreline change along wave runup-dominated shorelines and develop a conceptual model that can be used to communicate the nature of these changes to coastal managers, planners, and engineers. TWL analyses were conducted following a response-based TWL analysis that leveraged wave and water level datasets compiled as part of FEMA's California Coastal Analysis and Mapping Project (CCAMP) Open Pacific Coast (OPC) Study (www.r9coastal.org). The CCAMP OPC Study compiled a 50-year hourly hindcast of wave and water level conditions which was analyzed to estimate existing conditions 1-percent-annual-chance TWLs to inform coastal floodplain mapping for flood insurance rating purposes. The CCAMP OPC Study analysis framework was extended to include the effect of SLR and shoreline change to estimate future conditions TWLs by BakerAECOM (2015). The sections below describe the application of those methods to the present study.

Calculation of Wave Setup and Runup

A variety of methods are available for the calculation of wave setup and runup depending on shoreline and wave characteristics. These methods applied in this study range from empirical relationships based on field measurements (Stockdon) to laboratory-derived equations (TAW) and numerical models (DIM). These methods were adopted for estimation of wave setup and runup for this evaluation as follows:

- Sandy beaches and dunes: Stockdon et al. (2006)
- Coastal bluffs, cliffs, and coastal structures: Parametric Direct Integration Method (DIM) (FEMA 2005) for wave setup and TAW (van der Meer 2002) for wave runup

The primary input variables for wave setup and runup equations are typically wave height, period, roughness, and slope. Slope is defined differently for each equation and is either taken as the nearshore profile slope (DIM), foreshore beach slope (Stockdon), or barrier face slope (TAW).

Another key difference between the equations is the definition of wave height. While all three equations use the significant wave height (H_{m0}) parameter, the Stockdon and DIM equations use a deepwater wave height while the TAW equation uses a wave height at the toe of the bluff, cliff, or structure (Figure 3). This difference has important implications for wave runup response to SLR because the effect of SLR on the offshore wave height is negligible whereas its effect on the toe wave height can be substantial. This means that future conditions wave runup calculations based on the Stockdon et al. (2006) equation, as applied in this study, will predict a linear increase in TWL with respect to SLR, whereas calculations based on the TAW (van der Meer 2002) equation may predict a non-linear increase in TWL. This is because SLR may increase the depth of inundation at the toe of the barrier, which may allow a larger depth-limited wave to impact the barrier face and produce a larger runup (Chen and Alani 2012; Chen 2015; Kanoglu and Synolakis 1998).

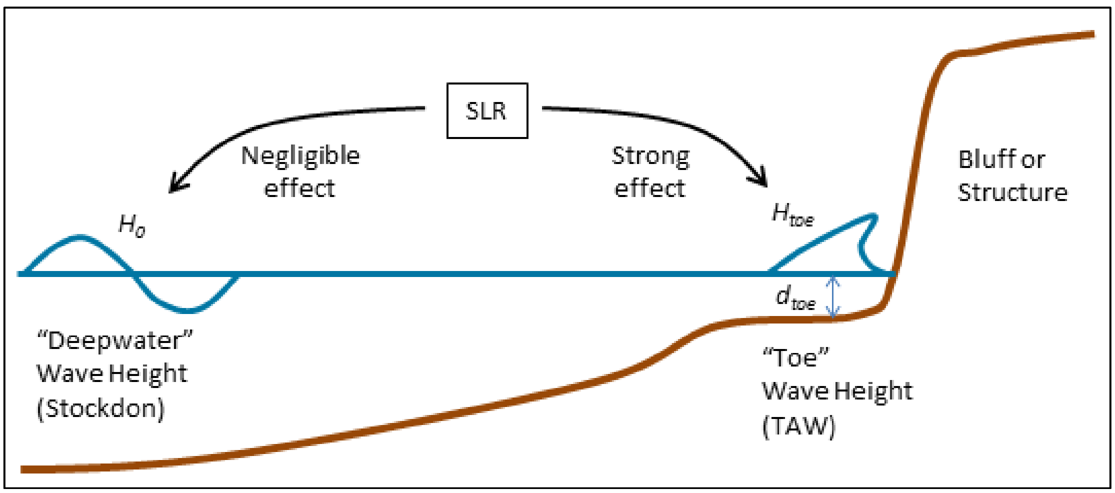

Figure 3. Wave Height Definition for Wave Runup Equations

Runup is directly proportional to the toe wave height in the TAW wave runup equation (Eq. 1), so an increase in water depth due to SLR will indirectly increase the wave runup because the deeper depth allows a larger depth-limited wave height. The predicted magnitude of this increase for the mid-range and high-range SLR scenarios (based on the TAW equation) will be derived in the results section of this paper.

$$R = H_{m0}\begin{bmatrix} 1.77\gamma_V\gamma_r\gamma_{other}\xi_{0m} & 0.5 \leq \xi_{0m} < 1.8 \\ \gamma_V\gamma_r\left(4.3 - \frac{1.6}{\sqrt{\xi_{0m}}}\right) & 1.8 \leq \xi_{0m} \end{bmatrix} \quad \text{(Eq. 1)}$$

where:

R is the 2% exceedance runup

H_{mo} = spectral significant wave height at the barrier toe

γ_v = reduction factor for influence of vertical walls

γ_r = reduction factor for influence of surface roughness

γ_{other} = reduction factor for influence of berm, angled wave attack, and structure permeability

ξ_{0m} = Iribarren, or surf similarity parameter, defined as $\xi_{0m} = m_{face}/\sqrt{H_{toe}/L_{0m}}$; L_{0m} is the deepwater wave length based on the $T_{m-1.0}$ wave period

Framework to Evaluate Future Flood Hazards

SLR and shoreline change were assumed to exert an influence on both the *vertical* change in TWL and the *horizontal* extent of coastal flood hazards (Figure 4). The *vertical* response is due to two primary factors: (1) SLR, which increases the base water level upon which wave runup processes are occurring (the linear effect) and (2) feedback processes at the toe of the backshore feature (bluff or structure) which further increase the TWL above the base SLR amount (the non-linear effect). The *horizontal* response is due to the overall profile adjustment to SLR, which results in a landward and upward shift of the profile. Bruun (1962) was the first to propose this concept and predictive equations relating equilibrium profile response to SLR; however, decades of research on this topic have not yet proven that the so-called “Bruun Rule” equation is a robust predictor of shoreline change (Komar 1998). Nevertheless, many investigators have recognized the utility of this overall conceptual model of profile retreat to SLR (Bray and Hooke 1997; Bruun 1983; Dean and Dalrymple 2002) and the basic premise that an erodible profile will respond to an increase in mean sea level through landward and upward adjustment is adopted for this assessment.

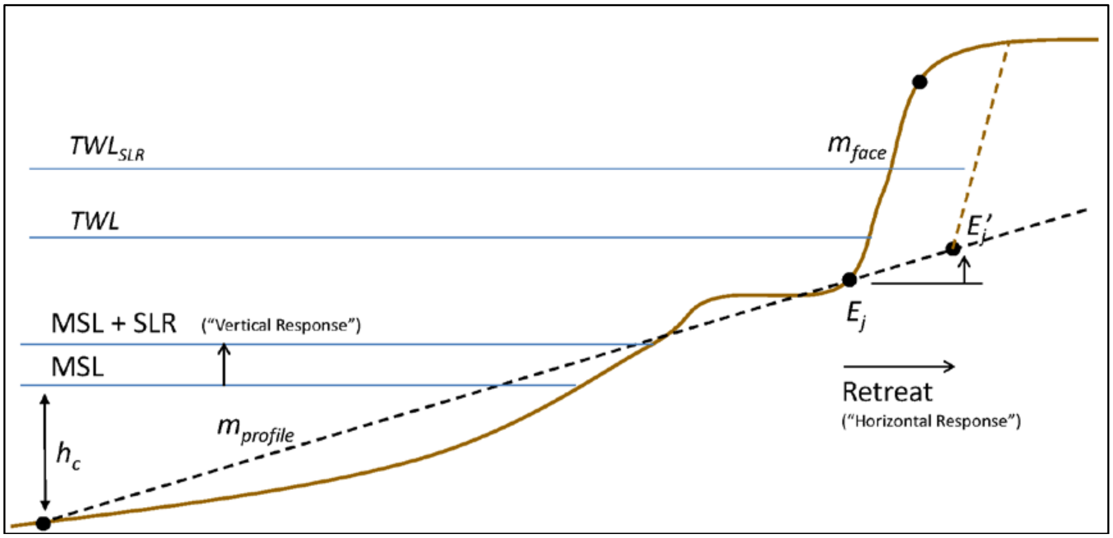

Figure 4. Vertical (SLR) and Horizontal (Shoreline Change) Effects on Coastal Flood Hazards

Future conditions 1-percent-annual-chance TWLs were estimated to evaluate the effect of including SLR and shoreline change in TWL calculations for static shorelines and shorelines with low and high erodibility. Profile characteristics are described below for three representative shoretypes and photographs are shown in Figure 5.

- Static: Low bluff with revetment; narrow beach; intertidal toe
- Low erodibility: Tall rocky cliff composed of resistant greywacke sandstone; narrow beach; intertidal toe; historical shoreline change rate of -0.2 ft/yr
- High erodibility: Tall erodible bluff composed of weakly consolidated sandy material; fronting beach; supratidal toe; historical shoreline change rate of -1.4 ft/yr

Figure 5. Photographs of Static (Revetment), Low Erodibility (Rocky Cliff), and High Erodibility (Sandy Bluff) Shorelines Evaluated for this Study

Elevation profiles for the low and high erodibility cases were adjusted to account for future shoreline change using the methods described in BakerAECOM (2015). Future shoreline change projections were developed using a simplified hybrid approach which pro-rated historical shoreline change rates using a "SLR Factor" to obtain estimates of future retreat rates. The SLR Factor was assumed to be proportional to the ratio of the future to historical rate of SLR (S_f/S_h) with an adjustment for a damped response as described by Ashton et al. (2011). Projected shoreline change distances for the low and high erodibility profiles are shown Table 2 for the mid-range (1-ft at 2050 and 3-ft at 2100) and high-range (2-ft at 2050 and 5.5-ft at 2100) SLR scenarios. The bluff and cliff profiles were adjusted as shown in Figure 4 by migrating the toe elevation (E_j) landward and upward along the nearshore profile slope maintaining the existing face slope (m_{face}). Future conditions TWL calculations were performed on both the static and eroded profiles to facilitate comparison among the TWL results and evaluate the effect of shoreline change on future conditions TWLs.

Table 2. Projected Shoreline Change Distances for 2050 and 2100

	Mid-Range SLR		*High-Range SLR*	
Profile	*1 ft at 2050*	*3 ft at 2100*	*2 ft at 2050*	*5.5 ft at 2100*
Static (Revetment)	0	0	0	0
Low Erodibility (Sandy Bluff)	-11	-30	-15	-41
High Erodibility (Rocky Cliff)	-91	-257	-129	-348

RESULTS

This section presents results of the future conditions TWL analysis at representative shoretypes in response to SLR and shoreline change. The first section presents the predicted TWL response to SLR at representative static bluff, cliff, and structure shoretypes derived using the TAW equation without consideration of shoreline change. The second section presents the predicted future conditions TWL response at three example profiles considering the combined influence of SLR and shoreline change.

Predicted TWL Response at Representative Shoretypes without Shoreline Change

As discussed above, the TAW wave runup equation (Eq. 1) is directly proportional to the toe wave height, so an increase in toe water depth due to SLR will increase the wave runup on steep barriers. The TAW equation was evaluated across a range of toe wave height (H_{toe}), peak period (T_p), barrier face slope (m_{face}), and slope roughness (γ_r) values typical of the California coast to estimate the sensitivity of bluff, cliff, and structure shoretypes to SLR:

- H_{toe}: 1.0, 2.0, 3.0, 4.0, 5.0, 6.0 ft
- T_p: 12, 15, 18 sec
- m_{face}: 26, 45, 80 deg or 2:1, 1:1, 0.18:1 (horizontal:vertical)
- Rougness: γ_r = 1.0 (smooth), γ_r = 0.8 (rocky), and γ_r = 0.6 (armored)
- Depth-limited breaking criterion: $H_{toe} = 0.78 \times d_{toe}$
- Shoreline change: no shoreline change considered (static profile)

The results are presented in terms of the predicted increase in TWL per unit SLR, referred to as the "TWL amplification factor." The TWL amplification factor is defined as the ratio of the TWL increase to the amount of SLR,

$$TWL\ Amplification\ Factor = \Delta TWL / SLR \qquad \text{(Eq. 2)}$$

where ΔTWL is the difference between the existing and future conditions 1-percent-annual-chance TWL. The TWL amplification factor can also be interpreted as the predicted increase in TWL per foot of SLR. Predicted TWL amplification factors based on the TAW equation are presented in Table 3 for static (non-eroded) profiles.

The average predicted TWL amplification factors range from approximately two to three depending on slope roughness, meaning that wave runup is predicted to increase by approximately double or triple the amount of SLR when using the TAW equation.

Table 3. Predicted TWL Amplification Factors for Static Shoretypes

	TWL Amplification Factor (ΔTWL/SLR)	
Shoretype	*Range*	*Average*
Smooth Slope	2.8-3.3	3.1
Rocky Slope	2.3-2.6	2.5
Armored or Vertical Slope	1.7-2.0	1.8

Notes: Based on TAW (van der Meer 2002) wave runup equation. Amplification factors can be interpreted as the increase in TWL per 1 foot of SLR.

The TWL amplification factors can also be translated into relative increases in the TWL for a given amount of SLR using Eq. 2. Table 4 and Figure 6 show the predicted TWL increases in response to the NRC (2012) (a) mid-range and (b) high-range SLR projections for static shorelines with varying slope roughness. The lower limits of the ranges shown in Figure 6 correspond to a linear increase in TWL in response to SLR (i.e., TWL increase = SLR). The solid, dotted, and dashed lines within the range represent the average TWL increase for the armored, rocky, and smooth slope cases. The TWL increases shown can also be thought of as the required increase in crest elevation of a coastal structure to maintain the same level of flood protection. The predicted TWL increases shown in Table 4 and Figure 6 capture only the increase in wave runup due to SLR and do not consider the influence of SLR on other hydrodynamic processes such as tidal range or wave setup.

Table 4. Predicted TWL Increase for Static Shoretypes

	TWL Increase (ft)			
Shoretype / SLR	*1 ft*	*2 ft*	*3 ft*	*5.5 ft*
Smooth Slope	2.5-3.5	5.5-6.5	8.5-10	15.5-18
Rocky Slope	2-2.5	4.5-5	7-8	12.5-14
Armored Slope or Vertical Wall	1.5-2	3.5-4	5-6	9.5-11

Notes: Based on TAW (van der Meer 2002) wave runup equation.

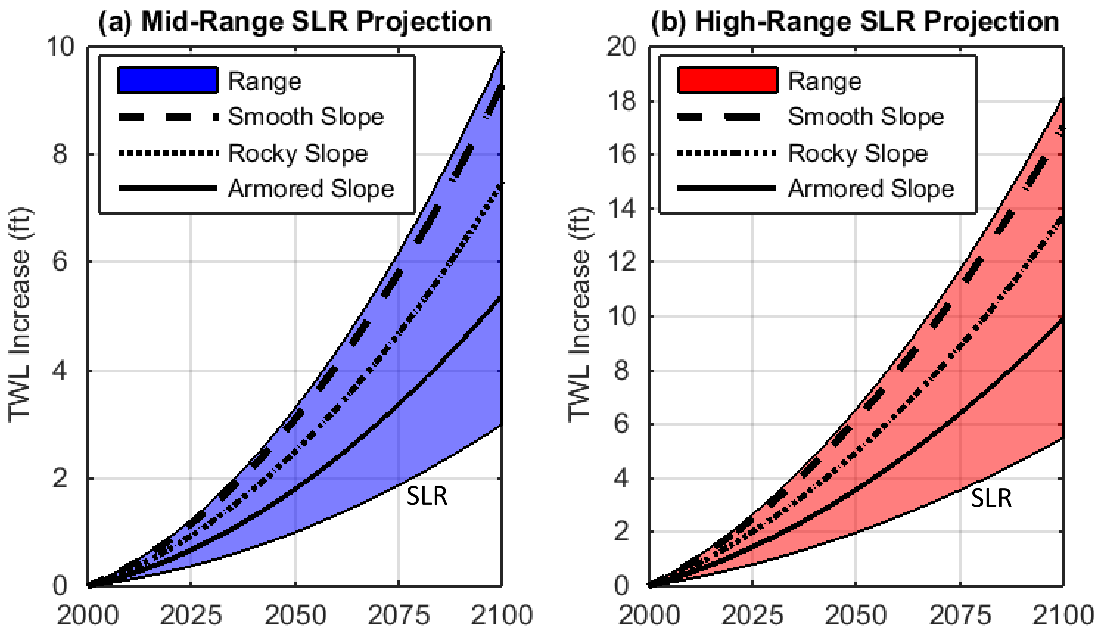

Figure 6. Predicted TWL Increase in Response to NRC (2012) Mid-Range and High-Range SLR Estimates for Static Shoretypes

Predicted TWL Response at Representative Shoretypes with Shoreline Change

The results presented above predict an increase in wave runup that is double to triple the amount of SLR at static bluff, cliff, and structure shoretypes. The predictive relationships derived above did not consider the mitigating effect of shoreline change, which can act to reduce the TWL amplification factor.

The results of the future conditions 1-percent-annual-chance TWL calculations with consideration of SLR and shoreline change are shown in Table 5 for the revetment, low erodibility cliff, and high erodibility bluff. Static (non-eroded) and eroded results are shown for the cliff and bluff profiles.

Table 5. TWL Response to SLR at Static Revetment, Low Erodibility Cliff, and High Erodibility Bluff

SLR	*Revetment (Static) ΔTWL (ft)*	*Cliff (Static) ΔTWL (ft)*	*Cliff (Eroded) ΔTWL (ft)*	*Bluff (Static) ΔTWL (ft)*	*Bluff (Eroded) ΔTWL (ft)*
1.0	2.2	3.7	3.7	1.0	1.0
2.0	4.3	6.5	6.1	2.9	2.0
3.0	6.3	8.9	8.0	7.3	3.0
5.5	12.9	16.2	15.0	17.8	5.5
Average TWL Amplification Factor	2.2	3.2	3.0	2.0	1.0

Note: *ΔTWL* indicates the difference between the existing and future 1-percent-annual-chance TWL.

The static profiles show strong non-linear TWL increases with average TWL amplification factors ranging from 2.0 to 3.2, indicating that the TWL increase is two the three times the amount of SLR. This TWL increase represents a worst-case condition because the static shorelines were not permitted to retreat in response to SLR. A similar result is observed at the static revetment profile; however, the TWL response is damped due to the rock armor roughness factor.

The effect of shoreline change in mitigating the TWL increase in response to SLR can be seen by comparing the static vs. eroded results. The decrease in TWL amplification at the low erodibility cliff profile is very minimal – the TWL amplification factor only decreases from 3.2 to 3.0. This is because the low erodibility shoreline cannot “keep pace” with SLR. In contrast, the decrease in TWL amplification at the high erodibility cliff profile is dramatic – the TWL amplification factor decreases from 2.0 to 1.0. This is because the high erodibility shoreline experiences rapid shoreline retreat and maintains an equilibrium position with respect to rising sea level (based on the shoreline change assumptions adopted for this study). The TWL at the eroded bluff profile assumes a linear response as a result. These results demonstrate the importance of including shoreline change in future conditions TWL calculations.

Future Conditions TWL Response to Physical Adaptation Strategies

The development of physical adaptation strategies is a common output from SLR vulnerability and risk assessments. For many coastal communities, structural alternatives may be the preferred option to mitigate the vertical increase in TWL due to SLR and horizontal increase in coastal flood hazards due to shoreline change. The TWL evaluations discussed above provide an initial assessment of the predicted TWL response to SLR for different shoretypes under different shoreline change conditions. Table 6 compares the TWL response to four hypothetical representative physical adaptation strategies for beach and bluff profiles: build a seawall, remove an existing revetment, modify an existing revetment, and install a new revetment. The adaptation strategies generally exhibit one of the following effects on the TWL response: shift TWL response from linear to non-linear, shift TWL response from non-linear to linear, or reduce the TWL amplification. The discussion section will synthesize the future conditions TWL findings to develop a conceptual model of TWL response to SLR, shoreline change, and physical adaptation strategies.

Table 6. TWL Response to Representative Physical Adaptation Strategies

Existing Shoretype	*Adaptation Strategy*	*Predicted Influence on TWL Amplification Factor*	*Notes*
Sandy Beach	Build seawall	Increase from 1.0 to 2.0	Construction of seawall shifts TWL response from linear to non-linear
Highly Erodible Bluff	Remove revetment / Managed retreat	Decrease from 2.2 to 1.0	Removal of revetment shifts TWL response from non-linear to linear

Existing Shoretype	*Adaptation Strategy*	*Predicted Influence on TWL Amplification Factor*	*Notes*
Bluff + revetment	Reduce revetment slope	Decrease from 2.3 to 1.9	Reduction in revetment slope from 2:1 to 3:1 decreases TWL amplification
Rocky cliff	Install revetment	Decrease from 2.5 to 1.8	Installation of revetment increases surface roughness and reduces TWL amplification

DISCUSSION

The TWL analysis presented above evaluated the response of future conditions TWLs to SLR, shoreline change, and physical adaptation strategies under a range of conditions. These findings were synthesized into a conceptual model of TWL response to SLR in wave runup-dominated environments. The conceptual model is shown in Figure 7 and shows the change in TWL as a function of SLR.

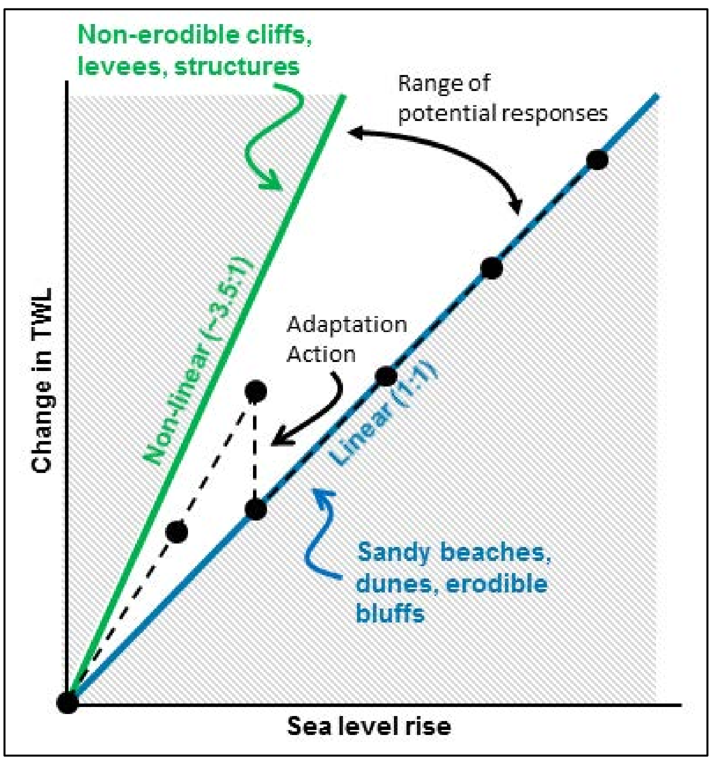

Figure 7. Conceptual TWL Response to SLR and Physical Adaptation Strategies

The conceptual model is represented by two bounding curves: the lower curve (in blue) is the linear (1:1) TWL response and the upper curve (in green) is the non-linear, amplified TWL response in which the TWL increase exceeds the amount of

SLR. The linear curve represents the dynamic shoretypes such as sandy beaches, dunes, and erodible bluffs that are predicted to exhibit a linear TWL response to SLR. The non-linear curve represents the static shoretypes such as resistant rocky cliffs and coastal structures that are predicted to exhibit an amplified, non-linear TWL response to SLR. Based on the TWL sensitivity testing and example cases presented above, the upper bound on the amplified response is estimated to be characterized by a TWL amplification factor of approximately 3.5. This represents a "worst-case" TWL response to SLR where the TWL increases substantially in response to future SLR.

The space between the curves represents the full range of potential outcomes between the amplified, non-linear response and the linear (1:1) response. Most moderately to highly erodible shorelines will likely fall within this range and exhibit TWL amplification factors between 1.0 and 3.5. Determining the exact magnitude of TWL increase requires a site specific evaluation; however, the results presented in this paper should provide some guidelines to facilitate informed, rapid estimates of future TWL increases in response to SLR and shoreline change or provide insights into some of the important considerations for a more rigorous assessment.

The TWL response to implementing a significant adaptation action at some point in the future – such as removing an existing revetment or seawall – is also shown in Figure 7 (black dashed line). Under this scenario, the TWL shifts from an amplified non-linear response to a linear response as a result of the adaptation action. The direction and magnitude of the TWL response shift as a result of adaptation actions depends on the nature of the physical adaptation strategy being implemented.

CONCLUSIONS

Various researchers have investigated the response of storm-surge dominated environments to SLR and suggested that some coastlines may experience a non-linear increase in storm water levels in response to SLR; however, fewer investigators have focused on wave runup-dominated shorelines. This paper extends the linear vs. non-linear characterization of storm surge response to characterize the TWL response to SLR and shoreline change. A "TWL Amplification Factor" ($\Delta TWL/SLR$) was introduced, which characterizes the increase in TWL per unit SLR. The study examined the TWL response along the California coastline which was taken to be representative of other wave runup-dominated environments. California state SLR guidance was applied to the TWL analysis at a variety of shoretypes, including revetments, rocky cliffs, erodible bluffs, and sandy shorelines to evaluate the future conditions TWL response to SLR and shoreline change.

The goal of the analysis was to develop a conceptual model of TWL response to SLR and shoreline change for different shoretypes in runup-dominated environments. Rule-of-thumb estimates of TWL amplification and TWL increase for static shoretypes in response to SLR were derived using the TAW equation. The results suggest a worst-case upper limit TWL amplification factor of approximately 3.5 for non-linear response to SLR. TWL analyses were then conducted to evaluate the response of shorelines to SLR and shoreline change and it was concluded that profile retreat is one mechanism by which natural shorelines mitigate the TWL amplification in response to SLR. The results suggested that static, low erodibility shorelines may experience the highest TWL amplification factors (on the order of 2.0 to 3.0) while more dynamic, moderate or high erodibility shorelines may experience linear or near-linear responses.

A high level examination of the effect of potential physical adaptation strategies in either increasing or decreasing the TWL amplification in response to SLR demonstrated the relative effectiveness of various actions, such as construction of a new revetment or seawall, removal of an existing structure, or modification of an existing structure's geometry.

The findings of the TWL analysis and conceptual model can be combined with existing conditions TWL estimates to provide coastal asset managers an easily implemented tool to perform a high level assessment of their shorelines to determine under which future SLR scenarios coastal protection features may become vulnerable to overtopping, inland flooding, and coastal structure failure. Further, the findings can be used to communicate the implications of implementing various physical adaptation strategies to reduce exposure to coastal hazards and to inform better decision making in the face of changing coastal conditions due to climate change.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of Erica Harris, Jose (Ricky) Torres-Cooban, and Sarah Kassem, who assisted with the shoreline change and wave runup analysis in support of this study.

REFERENCES

AECOM, Arcadis, Geografika, and 3D Visions (2011). Adapting to Rising Tides Transportation and Risk Assessment Pilot Project. Prepared for Metropolitan Transportation Commission, Caltrans, Bay Conservation and Development Commission, and U.S. Department of Transportation Federal Highway Administration. November 2011.

Arns A., T. Wahl, S. Dangendorf, and J. Jensen (2015). The impact of sea level rise on storm surge water levels in the northern part of the German Bight. Coastal Engineering, Vol. 96. pp. 118-131.

Ashton, A.D., Walkden, M.J.A., and Dickson, M.E. (2011). Equilibrium responses of cliffed coasts to changes in the rate of sea level rise. Marine Geology. Vol. 284. pp. 217-229.

Atkinson, J., J.M. Smith, and C. Bender (2013). Sea-level rise effects on storm surge and nearshore waves on the Texas coast: influence of landscape and storm characteristics. Journal of Waterway, Port, Coastal and Ocean Engineering. Vol. 139. pp. 98-117.

BakerAECOM (2015). Sea Level Rise Pilot Study. Future Conditions Analysis and Mapping. San Francisco County, California. Prepared for: Federal Emergency Management Agency (FEMA) Region IX. December 2015.

Bilskie, M.V., S.C. Hagen, S.C. Medeiros, and D.L. Passeri (2014). Dynamics of sea level rise and coastal flooding on a changing landscape. Geophysical Research Letters. Vol. 41, pp. 927-934.

Bray, M.J. and Hooke, J.M. (1997). Prediction of soft-cliff retreat with accelerating sea-level rise. Journal of Coastal Research. Vol. 13, No. 2, pp. 453-467.

Bruun, P. (1983). Review of conditions for use of the Bruun Rule of erosion. Coastal Engineering. Vol 7. pp 77-89.

Bruun P. (1962). Sea-level rise as a cause of shore erosion. America Society of Civil Engineers Proceedings. Journal Waterways and Harbors Division, 88, pp 117-130.

California Coastal Commission (CCC) (2015). Sea-Level Rise Policy Guidance. Interpretive Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits. August 12, 2015. Retrieved from: http://www.coastal.ca.gov/climate/slrguidance.html.

Chen, H.P. and A. Alani (2012). Reliability and optimized maintenance for sea defenses. Maritime Engineering. Vol. 165, Issue MA2. pp. 51-63.

Chen, H.-P. (2015). Maintenance of earth sea dykes in changing environmental and structural conditions. Proceedings of: The Fourth International Symposium on Life-Cycle Civil Engineering. Edited by: Furuta, H., D. Frangopol, and M. Akiyama. Life-Cycle of Structural Systems: Design, Assessment, Maintenance and Management. Tokyo, Japan, November 16-19, 2014.

Dean, R.G. and R. Dalrymple (2002). Coastal Processes with Engineering Applications. Cambridge University Press.

FEMA (2005). Final Draft Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States. February 2005.

Kanoglu, U. and C.E. Synolakis (1998). Long wave runup on piecewise linear topography. J. Fluid Mech. Vol. 374. pp. 1-28.

Knowles, N. (2010). Potential Inundation Due to Rising Sea Levels in the San Francisco Bay Region. San Francisco Estuary and Watershed Science 8(1).

Komar, P.D. (1998). Beach processes and sedimentation. Prentice-Hall. Upper Saddle River, NJ.

Holleman, R.C. and M.T. Stacey (2014). Coupling of Sea Level Rise, Tidal Amplification, and Inundation. Journal of Physical Oceanography. Vol. 44. pp. 1439-1455.

International Panel on Climate Change (IPCC). (2013). Climate Change 2013: The Physical Science Basis. Accessed at http://www.ipcc.ch/report/ar5/wg1/#.UpVXaOK3gyY.

Mousavi, M.E., J.L. Irish, A.E. Frey, F. Olivera, and B.L. Edge (2011). Global warming and hurricanes: the potential impact of hurricane intensification and sea level rise on coastal flooding. Climatic Change. Vol. 104, Issue 3, pp. 575-597.

National Research Council (2012). Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Prepared by the Committee on Sea Level Rise in California, Oregon, and Washington and the National Research Council Board on Earth Sciences and Resources and Ocean Studies Board Division on Earth and Life Studies.

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss (2012). Global

Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1. 37 pp.
Pethick, J. and J. Orford (2013). Rapid rise in effective sea-level in southwest Bangladesh: Its causes and contemporary rates. Global and Planetary Change. Vol. 111. pp. 237-245.
Quataert, E., C. Storlazzi, A. van Rooijen, O. Cheriton, and A. van Dongeren (2015). The influence of coral reefs and climate change on wave-driven flooding of tropical cyclones. Geophys. Res. Lett., Vol. 42, pp. 6407-6415.
RAMPP (2010). FEMA SLR Advisory Map Proof of Concept Study. Final Draft Report. November 30, 2010.
Revell, D.L, Battalio, B., Spear, B., Ruggiero, P., and Vandever, J. 2011. A methodology for predicting future coastal hazards due to sea-level rise on the California Coast. Climatic Change. December 2011.
Smith, J.M., M.A. Cialone, T.V. Wamsley, T.O. McAlpin (2010). Potential impact of sea level rise on coastal surges in southeast Louisiana. Ocean Engineering. Vol. 37, Iss. 1, pp. 37-47.
Stockdon, H.F., Holman, R.A., Howd, P.A., and Sallenger, A.H. (2006). Empirical parameterization of setup, swash, and runup. Coastal Engineering. Vol. 53. pp. 573-588.
Storlazzi, C.D., E. Elias, and P. Berkowitz (2015). Many Atolls May be Uninhabitable Within Decades Due to Climate Change. Nature Scientific Reports. Vol. 5, Article number 14546.
van der Meer, J. (2002). Technical Report. Wave Run-up and Wave Overtopping at Dikes. TAW, Technical Advisory Committee on Flood Defenses.